REFILL

WATER LEVEL

CYCLE TIMER

CYCLE TIMER

Homemaker™

REFILL

WATER LEVEL

CYCLE TIMER

CAUTION

- Do not turn the timer when it is on.
- Do not put your hands into the rotating tub.
- Do not sprinkle water over the control panel.
- Do not leave wet clothes on the control panel.

DANGER!

- The safety switch will stop the spinning operation automatically if the laundry load is unevenly distributed in the tub. Open the lid and redistribute the laundry evenly, then close the lid to restart.

- After use, turn off the water faucet and unplug the power cord.

REFILL

ATER LEVEL

CYCLE TIMER

SOAK

WASH
RINSE

DRAIN

SPIN

ON

OFF

3 5555 07042798 6

DALE R. PATRICK

ELECTRICAL POWER SYSTEMS TECHNOLOGY

Preface

Electrical Power Systems Technology provides a broad overview of the production, distribution, control, conversion, and measurement of electrical power. Through the presentation method used in this book, the reader will be able to develop an understanding of electrical power systems. The units of the book are organized in a systematic manner, beginning with electrical power production methods. The basic fundamentals of each major unit of the book are discussed at the beginning of the unit. These fundamentals provide a framework for the information which follows in each unit.

This book deals with many important aspects of electrical power, not just one or two areas. In this way, the reader can better understand the *total* electrical power system—from its production to its conversion to another form of energy. Each unit deals with a specific system, such as production, distribution, control, conversion, or measurement. Each system is broken down into subsystems. The subsystems are then explored in greater detail in the chapters which comprise each unit.

For more in-depth understanding of the content of this book, the reader should have a knowledge of basic electrical fundamentals. The mathematical presentations given are very simple and are used only to show practical relationships which are important in electrical power system operation. This book is recommended as a textbook for an "electrical power" or "electrical generators and motors" course. It would be a suitable text for vocational-technical schools, community colleges, universities, and, possibly, some technical high school programs. Many photographs and illustrations are shown to make the presentations that are given easier to understand. The content is presented in such a way that any reader should be able to learn a great deal about the operation of electrical power systems.

Stephen W. Fardo
Dale R. Patrick

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UNIT I

Power Production

The first unit of this book develops a framework for the units which follow. The fundamentals of power production are examined in Chapter 1. Electrical power production systems include modern power systems such as fossil-fuel (coal, oil, gas) systems, hydroelectric systems, and nuclear-fission systems. These systems are discussed in Chapter 2. However, there are also many alternative energy systems that are being studied as potential sources of electrical power. These alternative systems, which include nuclear-fusion, geothermal, solar, wind, fuel cell, coal gasification, tidal, and magnetohydrodynamic (MHD) systems, are discussed in Chapter 3.

Most of the electrical power that is produced is alternating-current (ac) power. Chapter 4 deals with the single-phase and three-phase alternators which are used to produce alternating-current (ac) power. Direct-current (dc) power can be produced by chemical action or rotating machinery, or it can be converted from ac sources (rectification). Chapter 5 deals with the systems used for production of direct current.

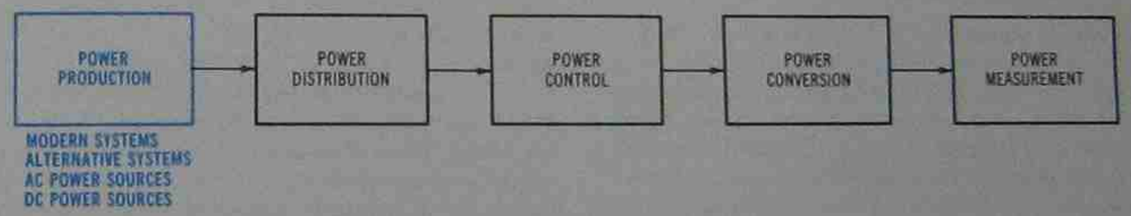


Fig. 1. The electrical power system.

CHAPTER 1

Power System Fundamentals

One of the most important areas of electrical knowledge is the study of electrical power systems. Complex power systems supply the vast need of our country for electrical energy. Due to our tremendous power requirement, we must constantly be concerned with the proper operation of our power production and power conversion systems. This book deals with some of the characteristics of electrical power production and power distribution systems, as well as the power control and power conversion systems needed. In addition, a discussion of electrical power measurement techniques is included.

THE ELECTRICAL POWER SYSTEM

The block diagram of an electrical power system is shown in Fig. 1-1. The first block or the *electrical power production* section is an important part of the complete electrical power system. However, once electrical power is produced, it must be distributed to the location where it will be used, so electrical *power distribution* systems (block 2) transfer electrical power from one location to another. Electrical *power control* systems (block 3) are probably the most complex of all the parts of the electrical power system as there are unlimited types of devices and equipment used to control electrical power. Then, the electrical *power conversion* systems (block 4), also called *loads*, convert the electrical power into some other form of energy, such as light, heat, or mechanical energy. Thus, conversion systems are an extremely important part of the electrical power system. Another part of the electrical power system is *power measurement* (block 5). Without electrical power measurement systems, control of electrical power would be almost impossible.

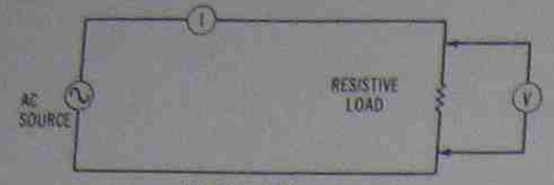
Each of the blocks shown in Fig. 1-1 represents one important part of the electrical power system. Thus, we should be concerned with each part of the electrical power system rather than only with isolated parts. In this way, we can develop a more complete understanding of how electrical power systems operate. This type of understanding is needed to help us solve our energy problems that are related to electrical power. We cannot consider only the production aspect of electrical power systems. We must understand and consider each part of the system.

TYPES OF ELECTRICAL CIRCUITS

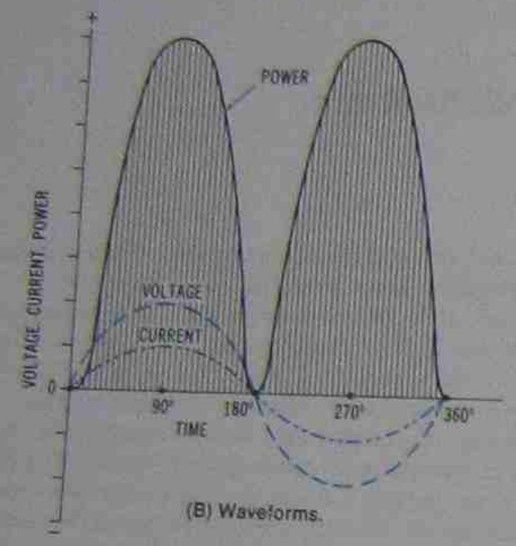
There are several basic fundamentals of electrical power systems. Therefore, the basics must be understood before attempting an in-depth study of electrical power systems. The types of electrical circuits associated with all electrical power production or power conversion systems are either resistive, inductive, or capacitive. Most systems have some combination of each of these three circuit types. These circuit elements are also called *loads*. A load is a part of a circuit that converts one type of energy into another type. A resistive load converts electrical energy into heat energy.

In our discussions of electrical circuits, we will primarily consider alternating-current (ac) systems at this time as the vast majority of the electrical power which is produced is alternating current. Direct-current (dc) circuits will be discussed later in greater detail in Chapter 5.

Fig. 1-1. Block diagram of an electrical power system.



(A) Circuit diagram.



(B) Waveforms.

(C) Vector representation.

Fig. 1-2. Resistive circuit.

Resistive Circuits

The simplest type of electrical circuit is a resistive circuit, such as the one shown in Fig. 1-2. The purely resistive circuit offers the same type of opposition to alternating-current power sources as it does to pure direct-current power sources. In dc circuits,

$$\text{Voltage (V)} = \text{Current (I)} \times \text{Resistance (R)}$$

$$\text{Current (I)} = \frac{\text{Voltage (V)}}{\text{Resistance (R)}}$$

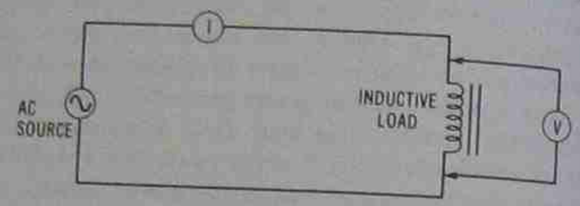
$$\text{Resistance (R)} = \frac{\text{Voltage (V)}}{\text{Current (I)}}$$

$$\text{Power (P)} = \text{Voltage (V)} \times \text{Current (I)}$$

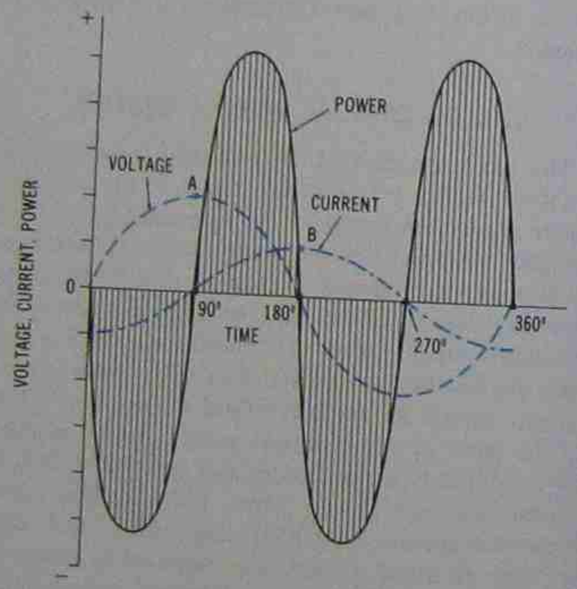
These basic electrical relationships show that when voltage is increased, the current in the circuit increases proportionally. Also, as resistance is increased, the current in the circuit decreases. By looking at the waveforms of Fig. 1-2B, we can see that the voltage and current in a purely resistive circuit, with ac applied, are in phase. An in-phase relationship exists when the minimum and maximum values of both voltage and current occur at the same time interval. Also, the power converted by the circuit is a product of voltage times current ($P = V \times I$). The power curve is also shown in Fig. 1-2B. Thus, when an ac circuit contains only resistance, its behavior is very similar to a dc circuit. Purely resistive circuits are seldom encountered in the design of electrical power systems, although some devices are primarily resistive in nature.

Inductive Circuits

The property of inductance (L) is very commonly encountered in electrical power systems. This circuit property, shown in Fig. 1-3, adds more complexity to the relationship between voltage and current in an ac circuit. All motors, generators, and transformers exhibit the property of inductance. This property is evident due to a counter-electromotive force (cemf) which is produced when a magnetic field is developed around



(A) Circuit diagram.



(B) Waveforms.

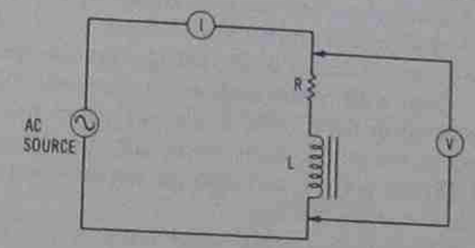
(C) Vector representation.

Fig. 1-3. Inductive circuit.

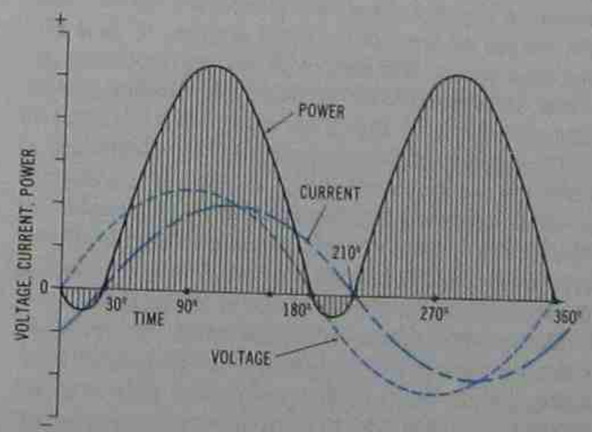
a coil of wire. The magnetic flux produced around the coils affects circuit action. Thus, the inductive property (cemf) produced by a magnetic field offers an opposition to change in the current flow in a circuit.

The opposition to change of current is evident in the diagram of Fig. 1-3B. In an inductive circuit, we can say that voltage leads current or that current lags voltage. If the circuit were purely inductive (contains no resistance), the voltage would lead the current by 90° (Fig. 1-3B) and no power would be converted in the circuit. However, since all actual circuits have resistance, the inductive characteristic of a circuit might typically cause the condition shown in Fig. 1-4 to exist. Here the voltage is leading the current by 30°. The angular separation between voltage and current is called the phase angle. The phase angle increases as the inductance of the circuit increases. This type of circuit is called a resistive-inductive (RL) circuit.

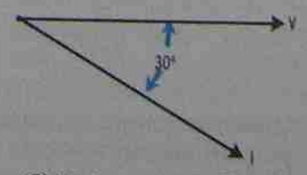
In terms of power conversion, a purely inductive circuit would not convert any power in a circuit. All



(A) Circuit diagram.



(B) Waveforms.



(C) Vector representation.

Fig. 1-4. Resistive-inductive (RL) circuit.

ac power would be delivered back to the power source. Refer back to Fig. 1-3B and note points A and B on the waveforms. These points show that at the peak of each waveform, the corresponding value of the other waveform is zero. The power curves shown are equal and opposite in value and will cancel each other out. Where both voltage and current are positive, the power is also positive since the product of two positive values is positive. When one value is positive and the other is negative, the product of the two values is negative; therefore, the power converted is negative. Negative power means that electrical energy is being returned from the load device to the power source without being converted to another form of energy. Therefore, the power converted in a purely inductive circuit (90° phase angle) would be equal to zero.

Compare the purely inductive waveforms to those of Fig. 1-4B. In the practical resistive-inductive (RL) circuit, part of the power supplied from the source is converted in the circuit. Only during the intervals from 0° to 30° and from 180° to 210° does negative power result. The remainder of the cycle produces positive power; therefore, most of the electrical energy supplied by the source is converted to another form of energy.

Any inductive circuit exhibits the property of inductance (L) which is the opposition to a change in current flow in a circuit. This property is found in coils of wire (which are called inductors) and in rotating machinery and transformer windings. Inductance is also present in electrical power transmission and distribution lines to some extent. The unit of measurement for inductance is the henry (H). A circuit has a 1-henry inductance if a current changing at a rate of 1 ampere per second produces an induced counterelectromotive force (cemf) of 1 volt.

In an inductive circuit with ac applied, an opposition to current flow is created by the inductance. This type of opposition is known as inductive reactance (X_L). The inductive reactance of an ac circuit depends upon the inductance (L) of the circuit and the rate of change of current. The frequency of the applied alternating current establishes the rate of change of the current. Inductive reactance (X_L) may be expressed as:

$$X_L = 2\pi fL$$

where,

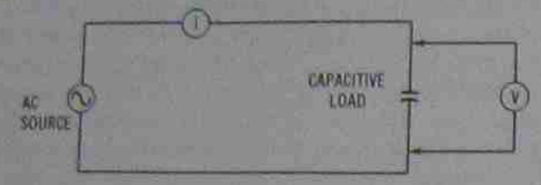
X_L is the inductive reactance in ohms,
2π is 6.28, the mathematical expression for one sine wave of alternating current (0°–360°),
f is the frequency of the ac source in hertz,
L is the inductance of the circuit in henrys.

Capacitive Circuits

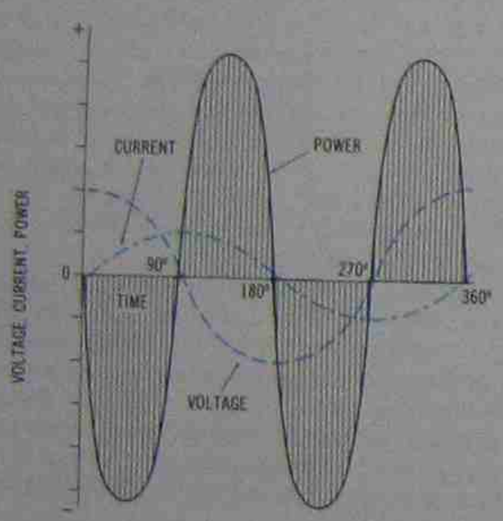
Fig. 1-5A shows a capacitive device connected to an ac source. We know that whenever two conductive

materials (plates) are separated by an insulating (dielectric) material, the property of capacitance is exhibited. Capacitors have the capability of storing an electrical charge. They also have many applications in electrical power systems.

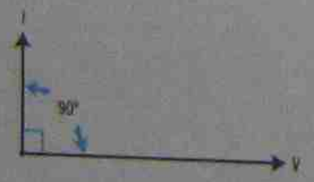
The operation of a capacitor in a circuit is dependent upon its ability to charge and discharge. When a capacitor charges, an excess of electrons (negative charge) is accumulated on one plate and a deficiency of electrons (positive charge) is created on the other plate. Capacitance (C) is determined by the size of the conductive material (plates) and by their separation (determined by the thickness of the dielectric or insulating material). The type of insulating material is also a factor in determining capacitance. Capacitance is directly proportional to the plate size and inversely proportional to the distance between the plates. The unit of capacitance is the farad (F). A capacitance of 1 farad results when a potential of 1 volt causes an electrical charge of 1 coulomb (a specific mass of electrons) to accumulate on a capacitor. Since the farad is a very large unit, microfarad (μF) values are ordinarily assigned to capacitors.



(A) Circuit diagram.



(B) Waveforms.



(C) Vector representation.

Fig. 1-5. Capacitive circuit.

If a direct current is applied to a capacitor, the capacitor will charge to the value of that dc voltage. After the capacitor is fully charged, it will block the flow of direct current. However, if ac is applied to a capacitor, the changing value of current will cause the capacitor to alternately charge and discharge. In a purely capacitive circuit, the situation shown in Fig. 1-5B would exist. The greatest amount of current would flow in a capacitive circuit when the voltage changes most rapidly. The most rapid change in voltage occurs at the 0° and 180° positions where the polarity changes. At these positions, maximum current is developed in the circuit. When the rate of change of the voltage value is slow, such as near the 90° and 270° positions, a small amount of current flows. In examining Fig. 1-5B, we can observe that current leads voltage by 90° in a purely capacitive circuit or the voltage lags the current by 90°. Since a 90° phase angle exists, no power would be converted in this circuit, just as no power was developed in the purely inductive circuit. As shown in Fig. 1-5B, the positive and negative power waveforms will cancel one another out.

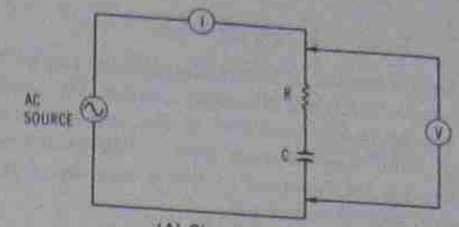
Since all circuits contain some resistance, a more practical circuit is the resistive-capacitive (RC) circuit shown in Fig. 1-6. In an RC circuit, the current leads the voltage by some phase angle between 0° and 90°. As capacitance increases, with no corresponding increase in resistance, the phase angle becomes greater. The waveforms of Fig. 1-6B show an RC circuit in which current leads voltage by 30°. This circuit is similar to the RL circuit of Fig. 1-4. Power is converted in the circuit except during the 0° to 30° interval and the 180° to 210° interval. In the RC circuit shown, most of the electrical energy supplied by the source is converted to another form of energy in the load.

Due to the electrostatic field which is developed around a capacitor, an opposition to the flow of alternating current exists. This opposition is known as capacitive reactance (X_C). Capacitive reactance is expressed as:

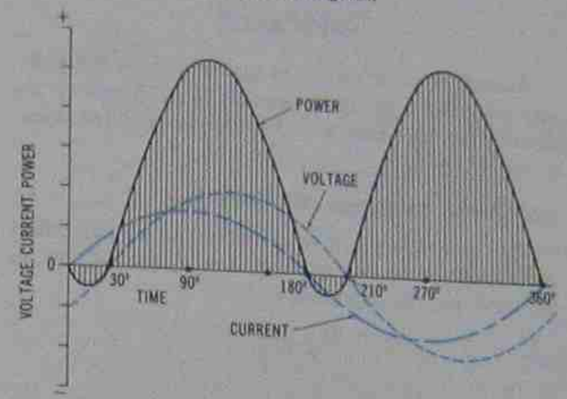
$$X_C = \frac{1}{2\pi fC}$$

where,

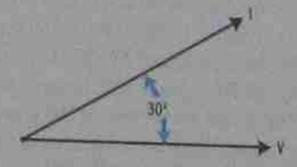
X_C is the capacitive reactance in ohms,
2π is the mathematical expression of one sine wave (0° to 360°),
f is the frequency of the source in hertz,
C is the capacitance in farads.



(A) Circuit diagram.



(B) Waveforms.



(C) Vector representation.

Fig. 1-6. Resistive-capacitive (RC) circuit.

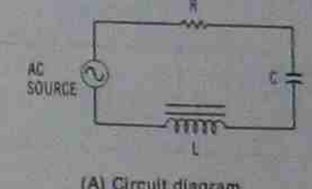
VECTOR AND PHASOR DIAGRAMS

In Figs. 1-3 through 1-6, a vector diagram was shown for each circuit condition that was illustrated. Vectors are straight lines which have a specific direction and length. They may be used to represent voltage or current values. An understanding of vector diagrams (sometimes called phasor diagrams) is important when dealing with alternating current. Rather than using waveforms to show phase relationships, it is possible to use a vector or phasor representation.

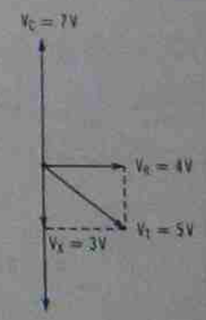
Ordinarily, when beginning a vector diagram, a horizontal line is drawn with its left end as the reference point. Rotation in a counterclockwise direction from the reference point is then considered to be a positive direction. Note that in the preceding diagrams, the voltage vector was the reference. For the inductive circuits, the current vector was drawn in a clockwise direction, indicating a lagging condition. A leading condition is shown for the capacitive circuits by the use of a current vector drawn in a counterclockwise direction from the voltage vector.

Use of Vectors for Series Circuits

Vectors may be used to compare voltage drops across the components of a series circuit containing resistance, inductance, and capacitance (an RLC circuit) as shown in Fig. 1-7. In a series ac circuit, the current is the same in all parts of the circuit and the voltages must be added by using vectors. In the example shown, specific values have been assigned. The voltage across the resistor (V_R) is equal to 4 volts, while the voltage across the capacitor (V_C) equals 7 volts, and the voltage across the inductor (V_L) equals 10 volts. We diagram the capacitive voltage as leading the resistive voltage by 90° and the inductive voltage as lagging the resistive voltage by 90°. Since these two values are in direct opposition to one another, they may be subtracted to find the resultant reactive voltage (V_X). By drawing lines parallel to V_R and V_X, the resultant voltage applied to the circuit can be found. Since these



(A) Circuit diagram.



(B) Vector diagram.

$V_L = 10V$
$V_X = V_L - V_C$
$= 10V - 7V$
$= 3V$

$V_T = \sqrt{V_R^2 + V_X^2}$
$= \sqrt{4^2 + 3^2}$
$= \sqrt{16 + 9}$
$= \sqrt{25}$
$= 5V$

(C) Problem solution.

Fig. 1-7. Voltage vector relationship in a series RLC circuit.

vectors form a right triangle, the value of V_T can be expressed as:

$$V_T = \sqrt{V_R^2 + V_X^2}$$

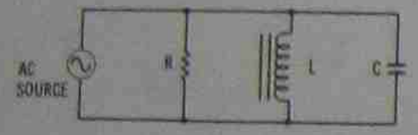
where,

V_T is the total voltage applied to the circuit,
V_R is the voltage across the resistance,
V_X is the total reactive voltage ($V_L - V_C$ or $V_C - V_L$, depending on which is the larger).

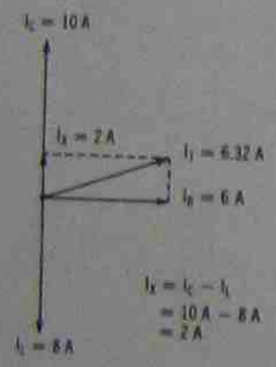
The solution to this problem is shown in Fig. 1-7C.

Use of Vectors for Parallel Circuits

Vector representation is also useful for parallel ac-circuit analysis. Voltage in a parallel ac circuit remains the same across all the components and the currents through the components of the circuit can be shown using vectors. A parallel RLC circuit is shown in Fig. 1-8. The current through the capacitor (I_C) is shown leading the current through the resistor (I_R) by 90°. The current through the inductor (I_L) is shown lagging I_R by 90°. Since I_L and I_C are 180° out of phase, they are subtracted to find the total reactive current (I_X). By drawing lines parallel to I_R and I_X, the total current of the circuit (I_T) may be found. These vectors form a right triangle; therefore, total current can be expressed as:



(A) Circuit diagram.



(B) Vector diagram.

$$I_T = \sqrt{I_R^2 + I_X^2}$$
$$= \sqrt{6^2 + 2^2}$$
$$= \sqrt{36 + 4}$$
$$= \sqrt{40}$$
$$= 6.32 \text{ A}$$

(C) Problem solution.

Fig. 1-8. Current vector relationship in a parallel RLC circuit.

$$I_T = \sqrt{I_R^2 + I_X^2}.$$

A similar method of vector diagramming can be used for voltages in RL and RC series circuits. This method may also be used for currents in RL and RC parallel circuits. RLC circuits were used in the examples to illustrate the method used to find a resultant reactive voltage or current in a circuit.

IMPEDANCE

Another application in the use of vectors is for determining the total opposition of an ac circuit to the flow of current. This total opposition is called impedance (Z).

Impedance in Series AC Circuits

Both resistances and reactances in ac circuits affect the opposition to current flow. Impedance (Z) of an ac circuit may be expressed as:

$$Z = \frac{V}{I}$$

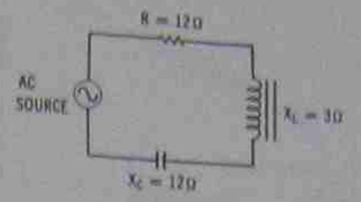
or

$$Z = \sqrt{R^2 + (X_L - X_C)^2}$$

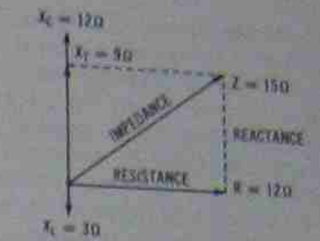
This formula may be clarified by using the vector diagram shown in Figure 1-9B. The total reactance (X_T) of an ac circuit may be found by subtracting the smallest reactance (X_L or X_C) from the largest reactance. The impedance of a series ac circuit is determined by using the preceding formula since a right triangle (called an impedance triangle) is formed by the three quantities which oppose the flow of alternating current. A sample problem for finding the total impedance of a series ac circuit is shown in Fig. 1-9D.

Impedance in Parallel AC Circuits

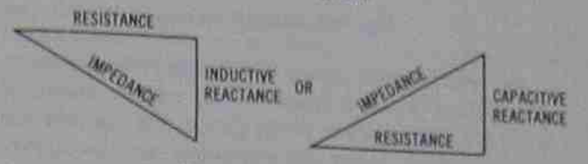
When components are connected in parallel, the calculation of impedance becomes more complex. Fig. 1-10A shows a simple RLC parallel circuit. Since the total impedance in the circuit is smaller than the resistance or reactance, an impedance triangle such as the one shown in Fig. 1-9C cannot be developed. A simple method used to find impedance in parallel circuits is the *admittance* triangle shown in Fig. 1-10B. The following quantities may be plotted on the triangle: admittance $= \frac{1}{Z}$, conductance $= \frac{1}{R}$, inductive susceptance $= \frac{1}{X_L}$, and capacitive susceptance $= \frac{1}{X_C}$. Notice that these quantities are the reciprocals of each type of opposition to alternating current. Therefore, since total impedance (Z) is the smallest quantity in a parallel ac circuit, it becomes the largest value on the admittance



(A) Circuit diagram.



(B) Vector diagram.



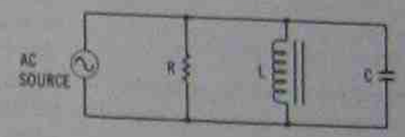
(C) Impedance triangles.

$$X_T = X_C - X_L$$
$$= 12\Omega - 3\Omega$$
$$= 9\Omega$$

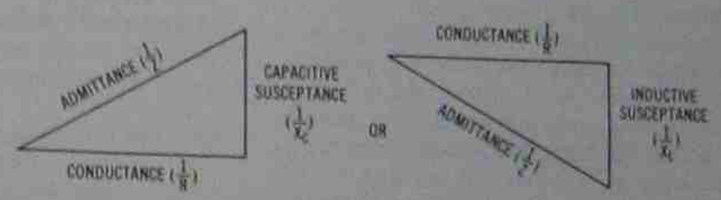
$$Z = \sqrt{R^2 + X_T^2}$$
$$= \sqrt{12^2 + 9^2}$$
$$= \sqrt{144 + 81}$$
$$= \sqrt{225}$$
$$= 15\Omega$$

(D) Problem solution.

Fig. 1-9. Impedance in series ac circuits.

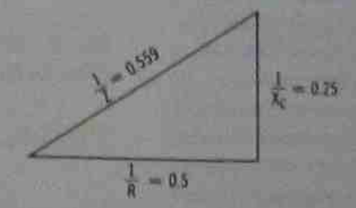


(A) Circuit diagram.



(B) Admittance triangles.

IF R = 2Ω, X_C = 4Ω. FIND Z



(C) Problem solution.

$$\frac{1}{Z} = \sqrt{(\frac{1}{R})^2 + (\frac{1}{X_C})^2}$$
$$= \sqrt{(0.5)^2 + (0.25)^2}$$
$$= \sqrt{0.25 + 0.0625}$$
$$= \sqrt{0.3125}$$
$$= 0.559$$
$$Z = \frac{1}{0.559}$$
$$= 1.79\Omega$$

Fig. 1-10. Impedance in parallel ac circuits.

triangle. The sample problem of Fig. 1-10C shows the procedure used to find total impedance of a parallel RC circuit.

POWER RELATIONSHIPS IN AC CIRCUITS

An understanding of basic power relationships in ac circuits is very important when studying complex electrical power systems. In the previous sections, resistive, inductive, and capacitive circuits were discussed. Also, power converted in these circuits was discussed in terms of power waveforms which were determined b the phase angle between voltage and current. In a c circuit, power is equal to the product of voltage an current ($P = V \times I$). This formula is true also fo purely resistive circuits. However, when a reactanc (either inductive or capacitive) is present in an a circuit, power is no longer a product of voltage an current.

Since reactive circuits cause changes in the metho used to compute power, the following described tech

niques express the basic power relationships in ac circuits. The product of voltage and current is expressed in volt-amperes (VA) or kilovolt-amperes (KVA), and is known as *apparent power*. When using meters to measure power in an ac circuit, apparent power is the voltage reading multiplied by the current reading. The actual power which is converted to another form of energy by the circuit is measured with a wattmeter. This actual power is referred to as *true power*. Ordinarily, it is desirable to know the ratio of true power converted in a circuit to apparent power. This ratio is called the *power factor* and is expressed as:

$$\text{pf} = \frac{\text{P}}{\text{VA}}$$

or

$$\%\ \text{pf} = \frac{\text{P}}{\text{VA}} \times 100$$

where,

pf is the power factor of the circuit,
P is the true power in watts,
VA is the apparent power in voltamperes.

The maximum value of power factor is 1.0, or 100%, which would be obtained is a purely resistive circuit. This is referred to as *unity power factor*.

The phase angle between voltage and current in an ac circuit determines the power factor. If a purely inductive or capacitive circuit existed, the 90° phase angle would cause a power factor of zero to result. In practical circuits, the power factor varies according to the relative values of resistance and reactance.

The power relationships we have discussed may be simplified by looking at the power triangle shown in Fig. 1-11. There are two components which affect the power relationship in an ac circuit. The in-phase (resistive) component which results in power conversion in the circuit is called *active power*. Active power is the true power of the circuit and is measured in watts. The second component is that which results from an inductive or capacitive reactance and is 90° out of phase with the active power. This component, called *reactive power*, does not produce an energy conversion in the circuit. Reactive power is measured in volt-amperes reactive (vars).

The power triangle of Fig. 1-11 shows true power (watts) on the horizontal axis, reactive power (var) at a 90° angle from the true power, and voltamperes (VA) as the longest side (hypotenuse) of the right triangle. Note the similarity between this right triangle, the voltage triangle for series ac circuits of Fig. 1-7, the current triangle for parallel ac circuits of Fig. 1-8, the impedance triangles of Fig. 1-9, and the admittance triangles of Fig. 1-10. Each of these right triangles has a horizontal axis that corresponds to the resistive component of the circuit, while the vertical axis corresponds

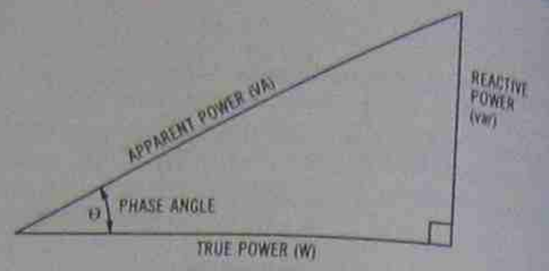


Fig. 1-11. Power triangle.

to the reactive component. The hypotenuse represents the resultant which is based on the relative values of resistance and reactance in the circuit. We can now see how important vector representation and an understanding of the right triangle are in analyzing ac circuits.

We can further examine the power relationships of the power triangle by expressing each value mathematically, based on the value of apparent power (VA) and the phase angle (θ). Remember that the phase angle is the amount of phase shift, in degrees, between voltage and current in the circuit. Trigonometric ratios, which are discussed in Appendix A, show that the sine of an angle of a right triangle is expressed as:

$$\text{sine } \theta = \frac{\text{opposite side}}{\text{hypotenuse}}.$$

Since this is true, the phase angle can be expressed as:

$$\text{sine } \theta = \frac{\text{reactive power (var)}}{\text{apparent power (VA)}}.$$

Therefore,

$$\text{var} = \text{VA} \times \text{sine } \theta.$$

We can determine either the phase angle or the var value by using the trigonometric tables.

We also know that the cosine of an angle of a right triangle is expressed as:

$$\text{cosine } \theta = \frac{\text{adjacent side}}{\text{hypotenuse}}.$$

Thus, in terms of the power triangle:

$$\text{cosine } \theta = \frac{\text{true power (W)}}{\text{apparent power (VA)}}.$$

Therefore, true power can be expressed as:

$$\text{W} = \text{VA} \times \text{cosine } \theta.$$

Note that the expression

$$\frac{\text{true power}}{\text{apparent power}}$$

is the power factor of a circuit; therefore, the power factor is equal to the cosine of the phase angle (pf = cosine θ).

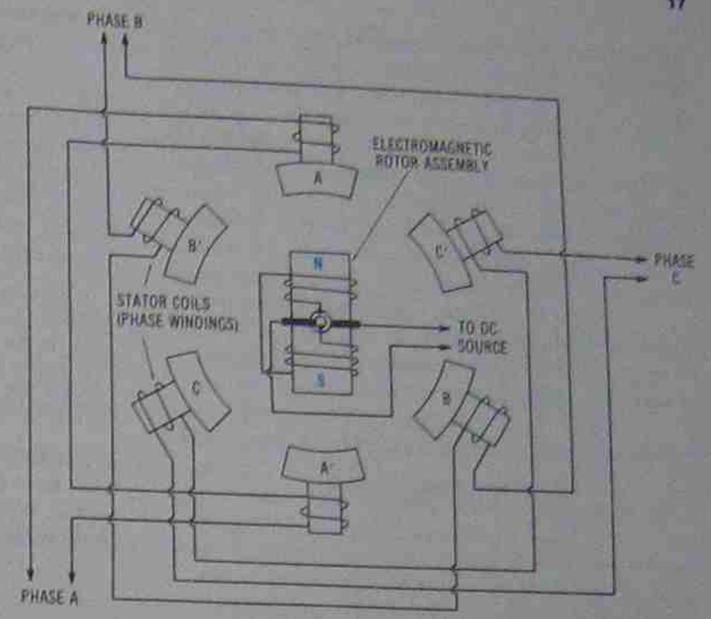


Fig. 1-12. Simplified drawing showing the basic construction of a three-phase ac alternator.

Right triangle relationships can also be expressed to determine the value of any of the sides of the power triangle when the other two values are known. These expressions are as follows:

$$\text{VA} = \sqrt{\text{W}^2 + \text{var}^2}$$

$$\text{W} = \sqrt{\text{VA}^2 - \text{var}^2}$$

$$\text{var} = \sqrt{\text{VA}^2 - \text{W}^2}$$

Appendix A should be reviewed in order to gain a better understanding of the use of right triangles and trigonometric ratios for solving ac circuit problems.

POWER RELATIONSHIPS IN THREE-PHASE CIRCUITS

To illustrate the basic concepts of three-phase power systems, we will use the example of a three-phase ac generator. This type of generator will be discussed in more detail in Chapter 4. A simplified pictorial diagram of a three-phase generator is shown in Fig. 1-12. A three-phase voltage diagram is shown in Fig. 1-13.

In Fig. 1-12, poles A′, B′, and C′ represent the beginnings of each of the phase windings, while poles A, B, and C represent the ends of each of the windings. These windings may be connected in either of two ways. These methods of connection, called the *wye* configuration and the *delta* configuration, are the basic types of three-phase power systems. These three-phase connections are shown schematically in Fig. 1-14. Keep

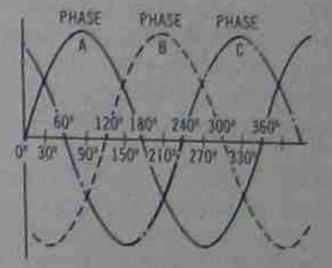


Fig. 1-13. Three-phase output waveform developed by an alternator.

in mind that these methods apply not only to three-phase ac generators, but also to three-phase transformer windings and three-phase motor windings.

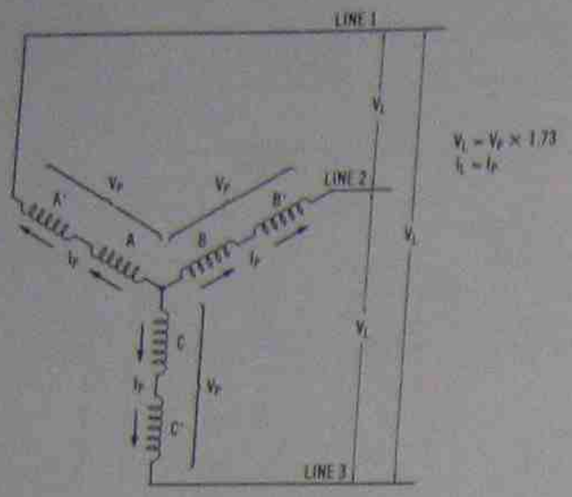
In the wye connection of Fig. 1-14A, the beginnings or the ends of each winding are connected together. The other sides of the windings become the ac lines from the generator. The voltage across the ac lines (V_L) is equal to the square root of 3 (1.73) multiplied by the voltage across the phase windings (V_P), or

$$\text{V}_\text{L} = \text{V}_\text{P} \times 1.73.$$

The line currents (I_L) are equal to the phase currents (I_P), or

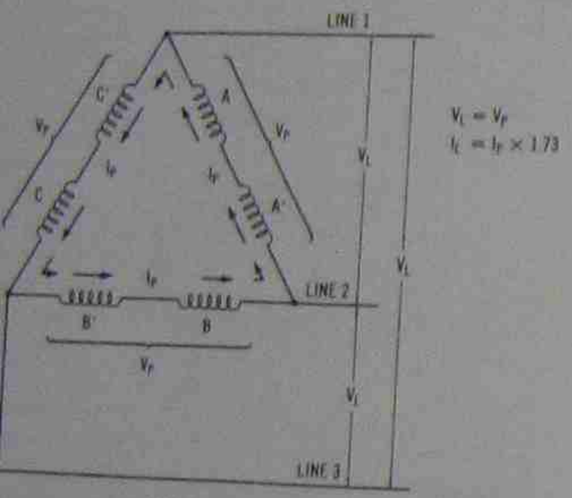
$$\text{I}_\text{L} = \text{I}_\text{P}.$$

In the delta connection of Fig. 1-14B, the end of one phase winding is connected to the beginning of the adjacent phase winding. The line voltages (V_L) are equal



$V_L = V_P \times 1.73$
$I_L = I_P$

(A) The wye (or star) connection.



$V_L = V_P$
$I_L = I_P \times 1.73$

(B) The delta connection.

g. 1-14. The two methods of connecting three-phase stator coils together.

the phase voltages (V_P). The line currents (I_L) are ual to the phase currents(I_P) multiplied by 1.73. The power developed in each phase (P_P) for either wye or a delta circuit is expressed as:

$$P_P = V_P \times I_P \times pf,$$

ere pf is the power factor of the load. The total wer (P_T) developed by all three phases of a three- se system is expressed as:

$$P_T = 3 \times P_P$$
$$= 3 \times V_P \times I_P \times pf$$
$$= 1.73 \times V_L \times I_L \times pf.$$

/e can summarize three-phase power relationships ollows:

$$\text{Voltamperes per phase } (VA_P) = V_P I_P$$
$$\text{Total voltamperes } (VA_T) = 3V_P I_P$$
$$= 1.73 V_L I_L$$
$$\text{Power factor (pf)} = \frac{\text{true power (W)}}{1.73 V_L I_L}$$
$$= \frac{W}{3V_P I_P}$$
$$\text{Power per phase } (P_P) = V_P I_P \times pf$$
$$\text{Total power } (P_T) = 3V_P I_P \times pf$$
$$= 1.73 V_L I_L \times pf$$

where,
V_L is the line voltage in volts,
I_L is the line current in amperes,
V_P is the phase voltage in volts,
I_P is the phase current in amperes.

Calculations involving three-phase power are somewhat more complex than for single-phase power calculations. We must keep in mind the difference between phase values and line values to avoid making mistakes.

SUMMARY

In this chapter, we have examined some of the basic fundamentals of electrical power systems. We need to have some understanding of the three basic types of circuits—resistive, inductive, and capacitive in order to understand the operation of power-producing systems, such as generators, chemical cells, and other power-conversion systems (such as electric lights and electric motors).

Resistive circuits exhibit similar characteristics with either applied ac or dc. The power converted in a resistive circuit is expressed in all cases as:

$$P = V \times I$$

The property of inductance is evident in systems due to coils of wire or windings which exhibit electromagnetic characteristics. The current developed in an inductive ac circuit *lags* behind the applied ac voltage due to this electromagnetic effect or counterelectromotive force (cemf). The power developed in an inductive circuit is dependent upon the power factor (pf) of the circuit. Power factor is a ratio of apparent power (voltamperes) and true power (watts) of a circuit and is expressed as:

$$pf = \frac{\text{true power}}{\text{apparent power}}.$$

Capacitance causes current to *lead* voltage in an ac circuit. The electrostatic field produced by a capacitor is responsible for this effect. The power developed in a capacitive circuit is expressed as:

$$P = V \times I \times pf$$

just as in an inductive circuit.

The power relationships, as well as voltage and current relationships in ac circuits, may be simplified by using vector or phasor diagrams. These diagrams allow us to examine by a visual analysis the effect of resistance, inductance, or capacitance on a circuit.

Both single-phase and three-phase ac power systems are used extensively. Electrical power systems involve:

1. Electrical power sources such as generators.
2. Distribution of electrical power, mainly by specialized conductors.
3. Control of electrical power by various methods.
4. Electrical power conversion systems or loads such as electrical lights and motors.
5. Measurement of electrical power-related quantities with specialized equipment.

The remaining chapters of this book discuss each of these five aspects of electrical-power systems.

POWER-RELATED TERMS

There are many power-related terms which are used in this book. Some of these terms are defined below so that you can refer to them later.

ampere—The amount of current which will flow when an electrical potential of one volt is applied to a circuit which has a resistance of one ohm.

apparent power (*VA*)—The amount of power which is delivered to a circuit or system; the product of applied voltage times the current (voltamperes).

British thermal unit (*Btu*)—The basic English unit of heat; the amount of heat which will raise the temperature of one pound of water one degree Fahrenheit (1° F); 1 Btu = 252 calories.

calorie—The basic metric unit of heat; the amount of heat required to raise the temperature of one gram of water one degree Celsius (1° C); 252 calories = 1 Btu.

conductor—A material, usually formed into round or rectangular shapes, which will allow electrical current to flow through it continuously.

current—The movement or flow of negatively charged particles, called electrons, through a conductor.

demand meter—A meter which is used to monitor the power demand of a system; it compares the peak power of the system to the average power.

energy—The amount of work that a system is capable of doing. There are several types, such as electrical, mechanical, light, and heat energy.

generator—A system or machine used to convert mechanical energy into electrical energy.

horsepower—The basic unit of mechanical power; 1 hp = 550 foot-pounds per second, or 746 watts.

insulator—A material which will not conduct electrical current under normal conditions.

motor—A machine which converts electrical energy into mechanical energy (torque).

ohm—The basic unit of resistance and impedance; the resistance of a material which with one ampere of current flowing through it will cause a voltage of one volt to appear across it.

ohmmeter—A meter used to make resistance measurements.

power—The rate at which work is done or energy is converted.

power factor—The ratio of true power (watts) converted in a circuit or system to the apparent power (voltamperes) delivered to the circuit or system.

reactive power (*var*)—The quantity of "unused" power which is developed by reactive components (inductive or capacitive) in an ac circuit or system. This unused power is delivered back to the power source since it is not converted to another form of power. The unit of measurement is the voltampere reactive (var).

resistance—The ability of a material, circuit, or system to oppose the flow of electrical current. The unit of measurement is the ohm.

torque—Mechanical energy in the form of a rotary motion.

true power (*watts*)—The amount of power which is converted to another form of energy in a circuit or system. It is measured with a wattmeter.

volt—The basic unit of voltage or potential difference in an electrical circuit.

voltage—The potential difference or electrical pressure across two points in a circuit; voltage causes current to flow in an electrical circuit.

watt—The basic unit of electrical power. The amount of power converted when one amp of current flows under a pressure of one volt.

wattmeter—A meter used to measure the electrical power that is converted in a circuit or system.

watt-hour meter—A meter which monitors electrical power used over a period of time.

PROBLEMS

1. A 20-μF capacitor and a 1000-ohm resistor are connected in series with a 120-volt 60-Hz ac source. Calculate:

   a. X_C
   b. Z
   c. I
   d. E_C
   e. E_R
   f. True power
   g. Apparent power
   h. Reactive power
   i. Power factor

   Draw an impedance triangle, a voltage triangle, and a power triangle for the circuit and label each value.

2. A circuit converts 12,000 watts of power. The applied voltage is 240 volts and the current is 72 amperes. Calculate:

   a. Apparent power
   b. Power factor
   c. Phase angle of the circuit

   Draw a power triangle for the circuit and label each value.

3. A 240-volt single-phase ac motor draws 20 amperes of current. Its power factor is 0.7 at the rated load. What is the true power converted? What is the value of reactive power? Draw a power triangle for the circuit and label each value.

4. A series circuit with 20 volts applied has a resistance of 100 ohms, a capacitance of 40 μF, and an inductance of 0.15 henry. Calculate:

   a. X_C
   b. X_L
   c. X_T
   d. Z
   e. I
   f. E_C
   g. E_L
   h. E_R
   i. The phase angle θ

   Draw an impedance triangle and a voltage triangle for the circuit and label each value.

5. Use the same values that were given for R, C, and L in Problem 4. Connect them in a parallel circuit that has 10 volts applied to it. Calculate:

   a. I_R
   b. I_C
   c. I_L
   d. I_T
   e. Z
   f. Conductance
   g. Susceptance
   h. Admittance
   i. Phase angle

   Draw a current triangle and an admittance triangle and label each value.

6. Use the series circuit of Problem 4. Calculate:

   a. True power
   b. Apparent power
   c. Reactor power
   d. Power factor

   Draw a power triangle and label each value.

7. Use the parallel circuit of Problem 5. Calculate:

   a. True power
   b. Apparent power
   c. Reactive power
   d. Power factor

   Draw a power triangle and label each value.

8. The meters on an industrial motor control panel show the following readings:

   Voltage = 120 volts
   Current = 12 amperes
   Power = 1 kW
   Frequency = 60 Hz

   Calculate:

   a. Apparent power
   b. Power factor
   c. The amount of capacitance which could be connected to the power lines to cause a power factor of 1.0.
   d. Circuit current after the capacitors are added.

9. A wye-connected three-phase ac generator has a phase voltage of 277 volts, line currents of 22 amperes per phase, and a power factor of 0.85. Calculate:

   a. Line voltage
   b. Power per phase
   c. Total power

10. A delta-connected three-phase ac generator has a line voltage of 240 volts, line currents of 12 amperes per phase, and a power factor of 1.0. Calculate:

    a. Phase current
    b. Power per phase
    c. Total power

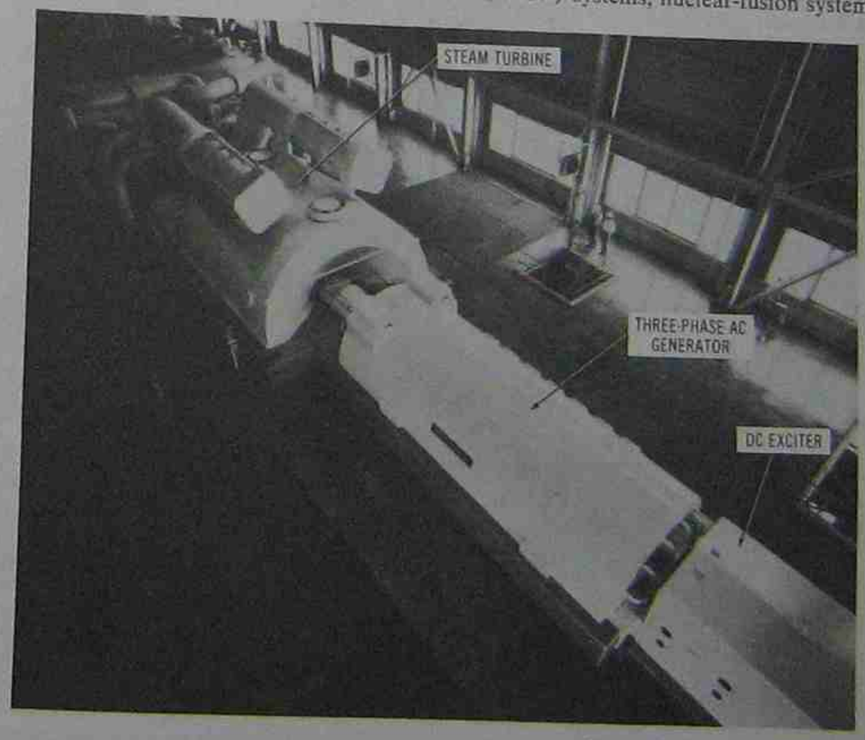
CHAPTER 2

Modern Power Systems

There are well over 80,000,000 customers of electrical utilities companies in the United States today. To meet this demand for electrical power, power companies combine to produce about two million-million ($2{,}000{,}000 \times 10^6$) kilowatt-hours of electrical power. This vast quantity of electrical power is supplied by about 4000 power plants. Individual generating units which supply over 1200 megawatts of electrical power are now in operation at some power plants.

Electrical power can be produced in many ways, such as from chemical reactions, heat, light, or mechanical energy. The great majority of our electrical power is produced by power plants located throughout our country which convert the energy produced by burning coal, oil, or natural gas, the falling of water, or from nuclear reactions into electrical energy. Electrical generators at these power plants are driven by steam or gas turbines or by hydraulic turbines, in the case of hydroelectric plants. This chapter will investigate the types of power systems that produce the greatest majority of the electrical power used today.

Various other methods, some of which are in the experimental stages, may be used as future power production methods. These include solar cells, geothermal systems, wind-powered systems, magnetohydrodynamic (MHD) systems, nuclear-fusion systems, and fuel cells.



Courtesy Westinghouse Electric Corp

Fig. 2-1. A steam turbine generator unit.

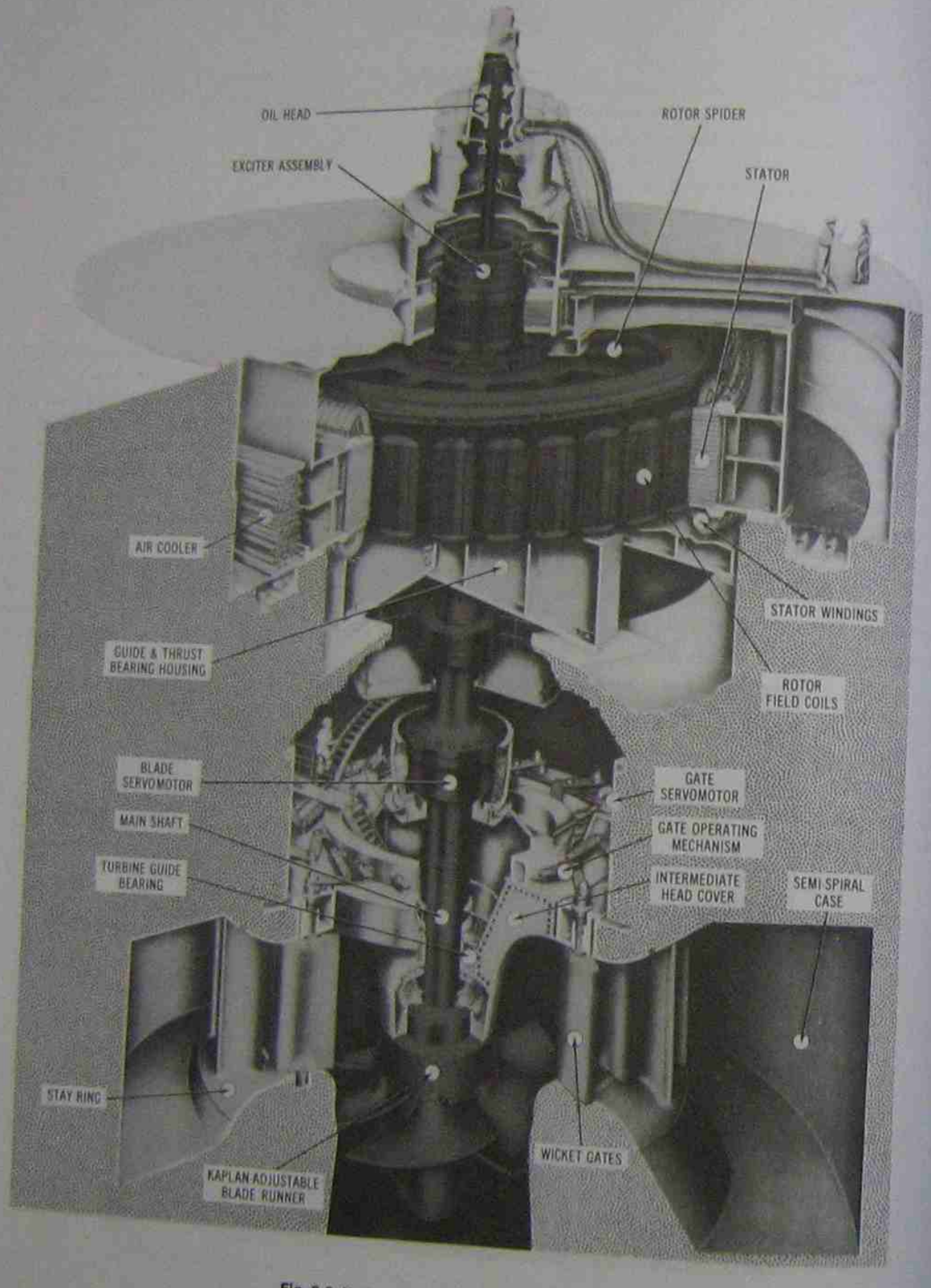


Fig. 2-2. Hydraulic turbine generator unit. Courtesy Allis-Chalmers Co

These alternative power systems will be discussed in greater detail in Chapter 3.

ELECTRICAL POWER PLANTS

Most electrical power in the United States is produced at power plants that are either fossil-fuel steam plants, nuclear-fission steam plants, or hydroelectric plants. A 390-megawatt steam turbine generator unit located at the Baltimore Gas and Electric Company is shown in Fig. 2-1. Fossil-fuel and nuclear-fission plants utilize steam turbines to deliver the mechanical energy needed to rotate the large three-phase alternators which produce massive quantities of electrical power. Hydroelectric plants ordinarily use vertically mounted hydraulic turbines, such as the one shown in Fig. 2-2. These units convert the force of flowing water into mechanical energy to rotate three-phase alternators.

The power plants may be located near the energy sources, near cities, or near the large industries where great amounts of electrical power are consumed. The generating capacity of power plants in the United States is greater than the combined capacity of the next four leading countries of the world. Thus, we can see how dependent we are upon the efficient production of electrical power.

Supply and Demand

The supply and demand situation for electrical energy is much different from other products which are produced by an organization and, then later, sold to consumers. Electrical energy must be supplied at the same time that it is demanded by consumers. There is no simple storage system which may be used to supply additional electrical energy at peak demand times. This situation is quite unique and necessitates the production of sufficient quantities of electrical energy to meet the demand of the consumers at any time. Accurate forecasting of load requirements at various given times must be maintained by utilities companies in order that they may recommend the necessary power plant output for a particular time of the year, week, or day.

Plant Load and Capacity Factors

There is a significant variation in the load requirement that must be met at different times. Thus, the power plant generating capacity is subject to a continual change. For the above reasons, much of the generating capacity of a power plant may be idle during low demand times. This means that not all the generators at the plant will be in operation.

There are two mathematical ratios with which power plants are concerned. These ratios are called load factor and capacity factor. They are expressed as:

$$\text{Load factor} = \frac{\text{Average load for a time period}}{\text{Peak load for a time period}}$$

$$\text{Capacity factor} = \frac{\text{Average load for a time period}}{\text{Output capacity of a power plant}}$$

It would be ideal, in terms of energy conservation, to keep these ratios as close to unity as possible.

FOSSIL FUEL SYSTEMS

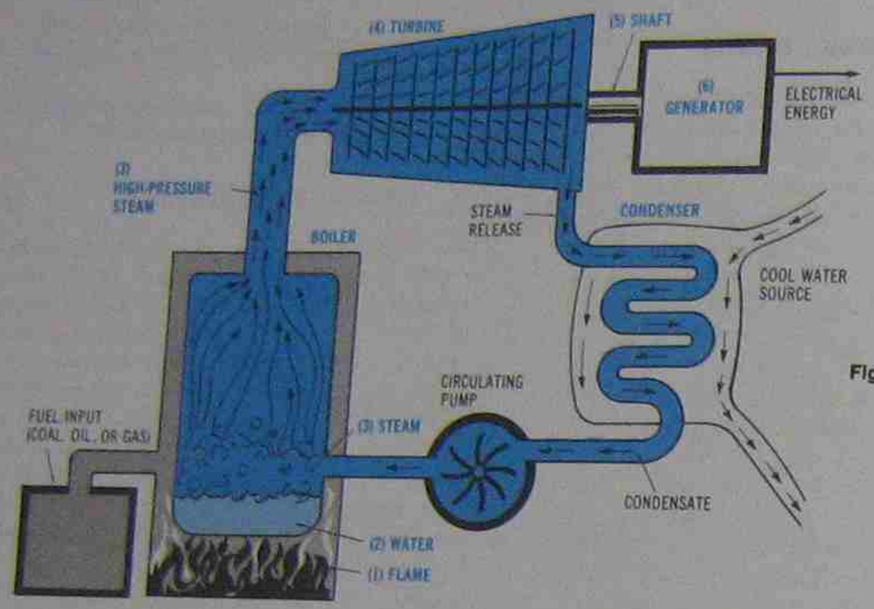
Millions of years ago, large deposits of organic materials were formed under the surface of the earth. These deposits, which furnish our coal, oil, and natural gas, are known as fossil fuels. Of these, the most abundant fossil fuel is coal and coal-fired electrical power systems produce about one-half of the electrical power used in the United States. Natural-gas-fired systems are used for about one-fourth of our electrical power, while oil-fired systems produce around 10% of the power at the present time. These relative contributions of each system to the total electrical power produced in the United States are subject to change due to the addition of new power generation facilities and fuel availability. At the present time, over 80% of our electrical energy is produced by fossil-fuel systems.

A basic fossil-fuel power system is shown in Fig. 2-3. In this type of system, a fossil fuel (coal, oil, or gas) is burned to produce heat energy. The heat from the combustion process is concentrated within a boiler where circulating water is converted to steam. The high-pressure steam is used to rotate a turbine. The turbine shaft is connected directly to the electrical generator and provides the necessary mechanical energy to rotate the generator. The generator then converts the mechanical energy into electrical energy. A commercial steam turbine-generator system is shown in Fig. 2-4. A gas turbine, which is used much less than the steam turbine, is shown in Fig. 2-5.

Fossil Fuels

Fossil fuels are used to supply heat by means of their chemical reactions for many different purposes. Such fuels contain carbon materials that are burned as a result of their reaction with air or oxygen. These fossil fuels are used as a direct source of heat when burned in a furnace and are used as a heat source for steam production when used in a power-plant boiler system. The steam that is generated is used for rotating the steam turbines in the power plants.

Fossil fuels vary according to their natural state (solid, liquid, or gas), according to their ability to produce heat, and in the type of flame or heat that they produce. Coal and coke are solid fossil fuels, with coal used extensively for producing heat to support elec



Heat from burning fuel (1) changes water in boiler (2) into steam (3), which spins turbine (4) connected by shaft (5) to generator (6), producing electrical energy.

Fig. 2-3. A basic fossil fuel power system.

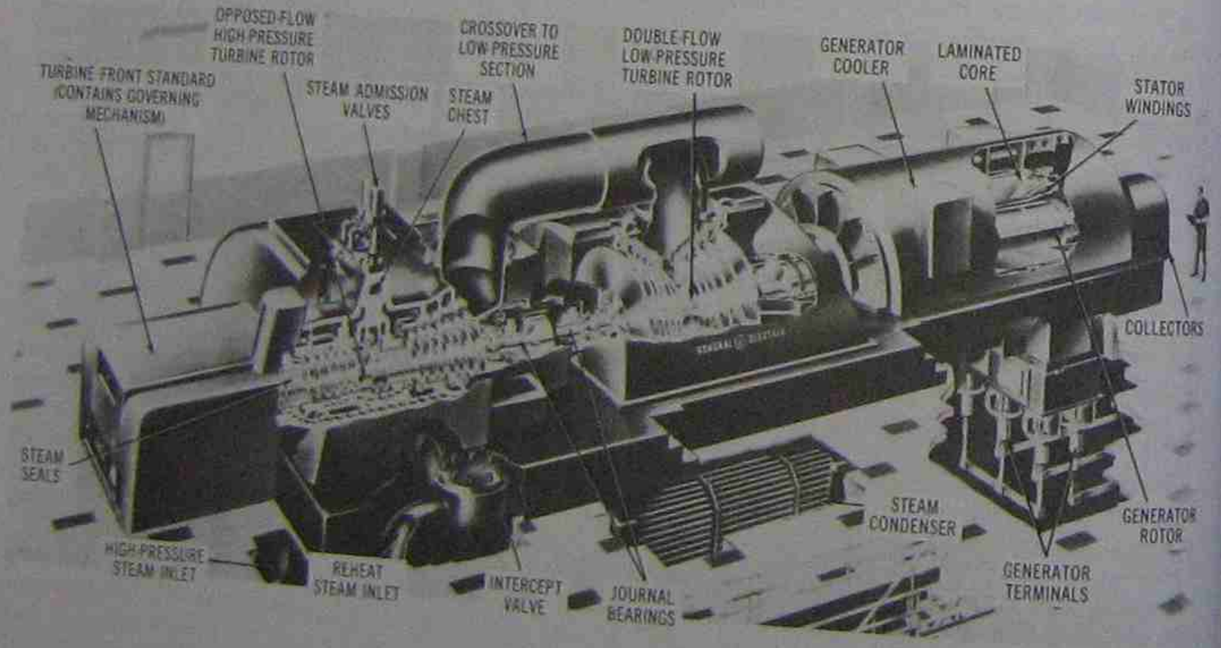


Fig. 2-4. A commercial steam turbine/generator system. Courtesy General Electric Co.

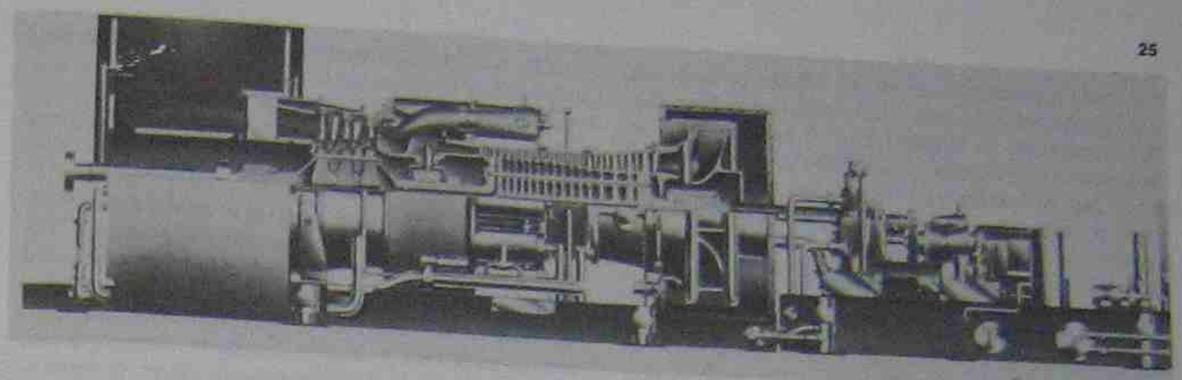


Fig. 2-5. Cutaway illustration of a gas turbine. Courtesy General Electric Co.

trical power production. Oil, gasoline, and diesel fuel, which are liquid fossil fuels derived by petroleum processing, are used mostly in conjunction with internal combustion engines. However, oil is used as a heat source for many power plants. Natural gas is the primary gaseous fuel used for electrical power production.

Coal-Fired Systems

The use of coal as a fuel to supply the necessary heat energy at a power plant requires the use of specialized stokers or grating units. These units reduce the size of the lump coal. Most of these units are mechanical systems which agitate the coal to reduce it into smaller lumps. The coal used at a power plant usually is sent through a stoker or grating unit by conveyor belts. A large gravity-feed hopper is often used to route very small lumps of coal into a pulverizing unit.

The pulverizer looks very similar in construction to a large ball-bearing unit. The coal is routed into the pulverizer unit where large rotating steel balls crush the coal until it is in particles about the same size and consistency as face powder. These fine particles are routed into the furnace by air pressure caused by forced-draft fans. The coal is held in suspension until it is ignited. It, then, releases a large amount of heat energy. The suspended powder-fine coal particles allow sustained combustion to take place in the furnace. The pulverized coal speeds up the combustion process.

Coal-Fired Plant Operation

Since the majority of electrical power produced today is from coal-fired systems, we will discuss the basic operation of this type of system. In a steam plant which produces electrical power, most of the operations are used for rotating the steam turbine. Remember, that in any steam plant, heat must be produced. This heat produces steam, which moves the steam turbine, which produces a rotary motion, and which, finally, produces electric power. The maximum efficiency of the coal-fired plant of today is approximately 40% when using a powdered-coal spraying process.

Coal requires extensive handling equipment. The coal itself must be handled and, then, the ash and dust particles must be removed. The coal is moved at the power plant to overhead hoppers by means of conveyor belts. These hoppers can be as large as eight stories high. The coal usually is fed into pulverizing mills by gravity. It is ground to a consistency similar to face powder using the method discussed previously. The powdered coal is then dried using plant exhaust gases and is then blown into a furnace. The coal is ordinarily blown through a tangential or "T" burner into the furnace. These burners are placed in the four corners of a square furnace to create the needed turbulence for complete combustion.

Another method of firing the furnace is the fluidized bed. An advantage of the fluidized bed is that it produces less pollution and can burn a lower quality coal. In a fluidized bed, coal is crushed to form ⅛-inch to ¼-inch diameter particles. When air is blown through a layer of this coal, the particles will float on a cushion of air. The pressure has to be adjusted very accurately so that the particles are fluidized without being blown away from the bed. The fluidized bed is the basis of a direct-combustion process. If the bed is hot enough, the flow of air through the bed leads to almost total combustion, and can provide a greater efficiency with less ash and dust.

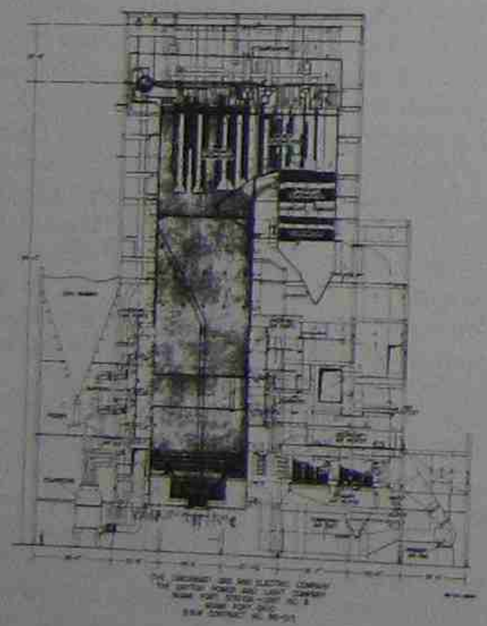
Power plant boilers, such as the one shown in Fig. 2-6, incorporate several special units to improve their thermal efficiency and economy of operation. An *economizer* is placed at the exhaust exit to preheat the water coming into the boiler. The economizer also preheats the air blowing into the furnace. A *superheater* is a bank of tubes located at the hottest spot of the furnace. These tubes take the steam after it leaves the boiler and before it enters the turbine. The purpose of the superheater is to raise the temperature of the steam.

Increased superheat decreases the percent of water per unit volume in the steam, which increases turbine life. A *desuperheater* is the next part of the system. The desuperheater brings the steam down to a temperature so it can be condensed. The *feedwater* in a power plant is used over and over with water added only to account for losses. The feedwater must be very pure to ensure long life of the boiler tubes.

After steam has been produced, a rotary motion must be developed. This rotary motion is produced by a steam turbine. A steam turbine, shown in Fig. 2-4, is made up of as many as 1500 blades. The rotor is usually divided into two parts—the high-pressure rotor and the low-pressure rotor. The low-pressure rotor is larger in diameter than the high-pressure rotor. Steam is channeled to the high-pressure rotor and it is then routed to the low-pressure rotor.

Steam turbines ordinarily achieve a maximum efficiency of between 20% to 28%, but only when run at very high speeds. Some turbines can produce as much as 160,000 horsepower. A speed of 3600 rpm is needed to develop a 60-Hz electrical power output. Large three-phase ac generators are connected to dc exciters. Generators are often cooled with hydrogen because hydrogen has less than 1/10 the density of water. Therefore, much less energy is required to recirculate the hydrogen for cooling purposes.

The process just described summarizes the operation of a steam power plant. There are several variations to the basic process; however, most plants use similar methods. The individual parts of a steam-generating system will be discussed in more detail in the following sections.



Courtesy Babcock & Wilcox Co.

Fig. 2-6. Natural circulation radiant boiler used by the Cincinnati Gas and Electric Company.

STEAM TURBINES

Steam turbine systems are used to produce over 80% of the electrical power used in the United States. The force of steam produces a rotary motion (mechanical energy) in a steam turbine. This mechanical energy is converted to electrical energy by using three-phase generators connected by a common shaft. Both fossil-fuel systems and nuclear-fission systems utilize steam turbines as prime movers (rotary motion producers).

A reaction turbine, such as the one shown in Fig. 2-4, channels high-velocity steam through a set of blades mounted on a rotary shaft. The reaction turbine usually has more than one set of blades, with each set having a different diameter. As the steam passes through the first section of blades, its pressure is reduced and its volume is increased. Due to the increased volume, the additional sections of blades must be of larger diameters and with longer sets of blades. These combined sections of blades direct the high-velocity steam in such a way that a maximum rotational force is produced by the turbine.

The design of a steam turbine is very critical for the efficient production of electrical power. Several characteristics of steam turbines cause design problems. Steam turbines must be operated at high rotational speeds, so the blades must be designed to withstand a tremendous amount of centrifugal force. The rotor and blade assemblies for steam turbines are usually machined from a forged piece of chromium and steel alloy. This assembly must be very precisely balanced before the machine is put into operation. The leakage of steam from the enclosed rotor and blade assembly must be prevented. Solid seals cannot be used along the rotor shaft so so-called "steam-seals" are used to provide a minimum clearance between the seals and the shaft. The bearings of a steam turbine must be carefully designed to withstand both axial and end pressures of high magnitudes.

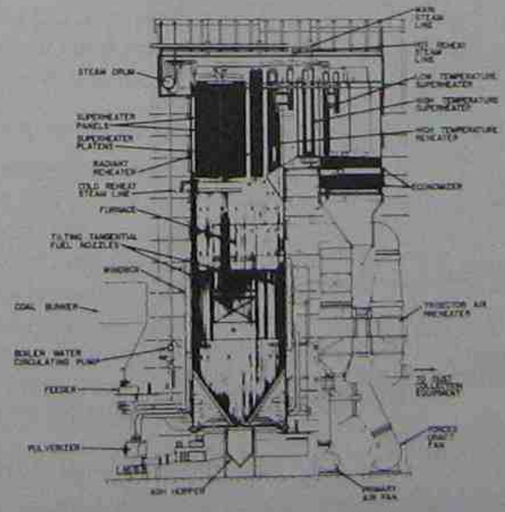
Steam turbines used in electrical power production must be rotated at a constant speed. If turbine speed changes, the frequency of the generator output voltage will be changed from the standard 60-Hz value. Therefore, a system of governors is used in a steam turbine to regulate its speed. The governor system adjusts the turbine speed by compensating for changes in generator power demand. As more load is placed on the generator (increased consumption of electrical power), the generator offers an increased resistance to rotation. Thus, power input to the turbine must be increased accordingly. The governor system of the turbine automatically adjusts the steam input to the turbine blades to compensate for increases and decreases in the load demand placed upon the generator which it drives.

BOILERS

Boilers (as shown in Figs. 2-7 and 2-8) are an important part of steam power production systems. The function of a boiler is to provide an enclosure in which pressurized water can be heated to a high temperature to produce steam. The heat from burning fossil or nuclear fuels is transferred to an area through which pressurized water flows and the water is converted to steam through this procedure.

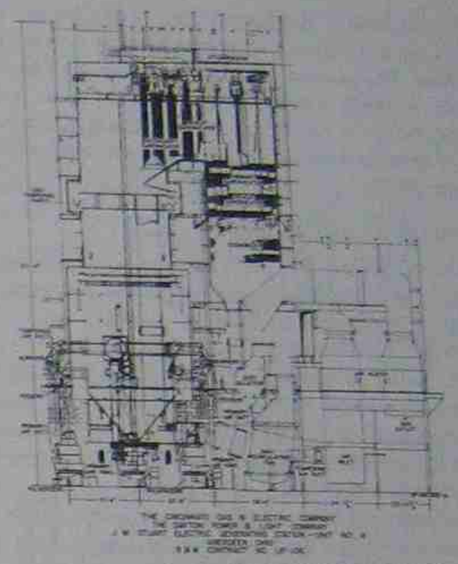
The transfer of heat within a boiler utilizes the three methods of heat transfer—radiation, convection, and conduction. The radiation method involves the movement of heat energy from a warm area to a cool area, and is dependent upon temperature difference and the ability of materials to absorb heat. The conduction method requires contact between the heat source and the heated area and relies upon the heat conductivity of the heated material. Convection is the movement of heat from a hot area to a cooler area by means of an intermediate substance, such as a gas. Each of these three methods of heat transfer occur in an operating boiler. However, they occur in varying amounts dependent upon boiler design.

A boiler which functions properly is a very critical part of the power production system as the boiler operation determines the quantity of steam available to produce the rotary motion of the turbine. When more power input for the generating process is required due to an increased load on the system, the boiler must deliver more steam to the turbine. Boilers must be able to provide effective water circulation, efficient fuel combustion, and maximum heat transfer to the circulating water. The boilers used in most steam power plants today are called water-tube boilers. Their design consists of banks of tubes, separated by heat insulation, through which water is circulated under high temperature and high pressure. Boiler design is very important for an efficient steam power-plant operation.



Courtesy Combustion Engineering, Inc.

Fig. 2-7. Tangentially-fired boiler.



Courtesy Babcock & Wilcox Co.

Fig. 2-8. Once-through universal boiler used at Dayton Power and Light Company.

Boiler Auxiliary Systems

There are several auxiliary systems used in a steam power plant to increase the operation and efficiency of the boilers. Some of these systems were mentioned briefly in previous sections. One auxiliary system is called an *economizer*. Economizers utilize the hot exhaust gases from the fuel reactions within a boiler to preheat the cold feedwater which is pumped into the boiler. Thus, the economizer uses the waste gases, which would otherwise be emitted through the exhaust stack, for an important purpose. This improves the efficiency of the power plant.

In addition to the economizer, feedwater *heaters* and *preheaters* are used to increase the water temperature before its entry into the boiler. These systems heat the pumped feedwater by means of steam which is circulated through the unit. In some plants, systems called *superheaters* are used. These units consist of banks of

tubes located at the hottest area of the boiler. Steam flows through these tubes before its entry into the steam turbine. The purpose of the superheater is to cause the steam to reach a higher temperature so as to produce more energy in the steam turbine. Each of these auxiliary systems helps to improve the efficiency of steam power plants.

Condensers and Purifiers

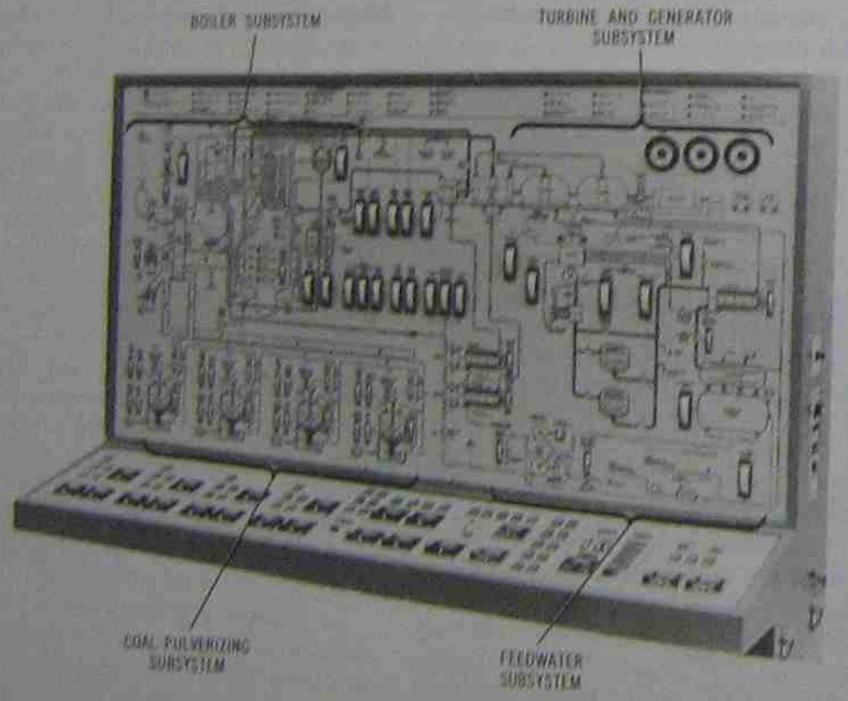
The condensers and feedwater purifiers used at steam power plants are also important in the production of energy. Condensers are used to cool the used steam which has passed through the steam turbine. The condensed water is continuously recirculated through the system. Feedwater purifiers are used to clean the impurities from the feedwater which is obtained from a water source located adjacent to the power plant. The feedwater purifiers play an important part in power plant operation. Without them, the metal used in the construction of the boiler would corrode, producing a slag build-up on the boiler walls, and eventually would destroy the boiler. Also, impurities in the steam can cause damage to the precision blades used in the steam turbines. In addition, the gases which are contained in the feedwater must also be removed. These gases are removed by a unit called a *deaerator*.

The quantity of feedwater which reaches the steam turbine in the form of steam is based on the amount of evaporation which takes place in the system. In the power plant, a comparative analysis must be made of the quantity of water entering the boiler and the quantity of steam coming out of the steam turbine. Adjustments in feedwater flow are based on this comparison.

FUTURE OF COAL-FIRED POWER SYSTEMS

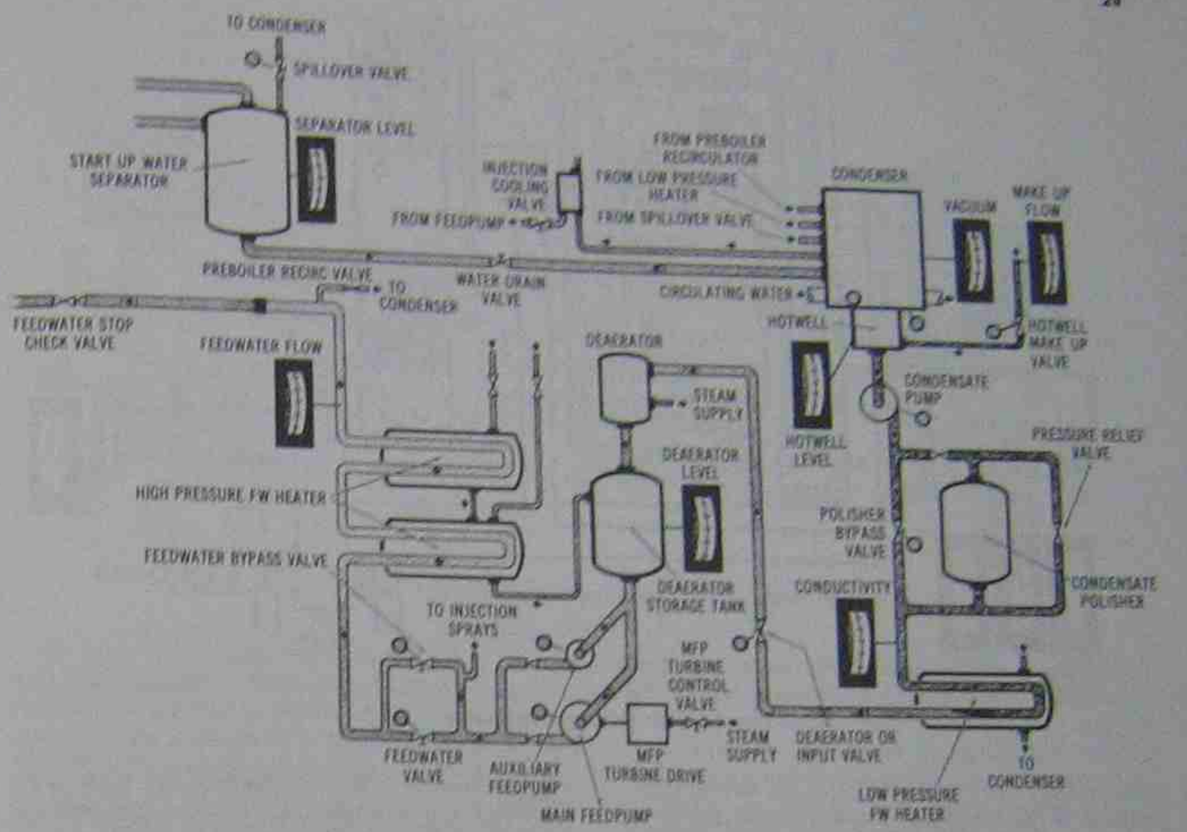
Pulverized-coal systems have been used for many years to produce energy for conversion to electrical power. However, there are now more environmental restrictions on these systems. The major problems are sulphur-dioxide and nitrogen-oxide emission controls for the power plants, particularly sulphur-dioxide controls. More stringent environmental controls increase the capital cost of power system operations. Even though coal is the most abundant fossil fuel, it is also the dirtiest in terms of environmental factors. Thus, a significant problem of electrical power technology is how to utilize coal in an environmentally acceptable way.

Electrical power systems are the largest consumers of coal in the United States. With a decrease in the availability of oil and natural gas fuels, coal must again



Courtesy Omnidata, Inc.

Fig. 2-9. A coal-fired electrical power system simulator.



Courtesy Omnidata, Inc.

Fig. 2-10. The feedwater subsystem.

be relied upon as the prime electrical power source of the future. Power production systems must be designed which will produce electrical energy in the most economical and environmentally attractive way.

Coal-Fired System Simulator

A coal-fired electrical power system simulator is shown in Fig. 2-9. Note how the various subsystems of the coal-fired power plant are interconnected within the overall system. There are basically five subsystems for this type of power plant. These subsystems are the feedwater system, the fuel and air system, the coal-pulverizing system, the boiler-water system, and the steam and turbine system. Each of these five subsystems is shown in the diagrams of Figs. 2-10 through 2-14.

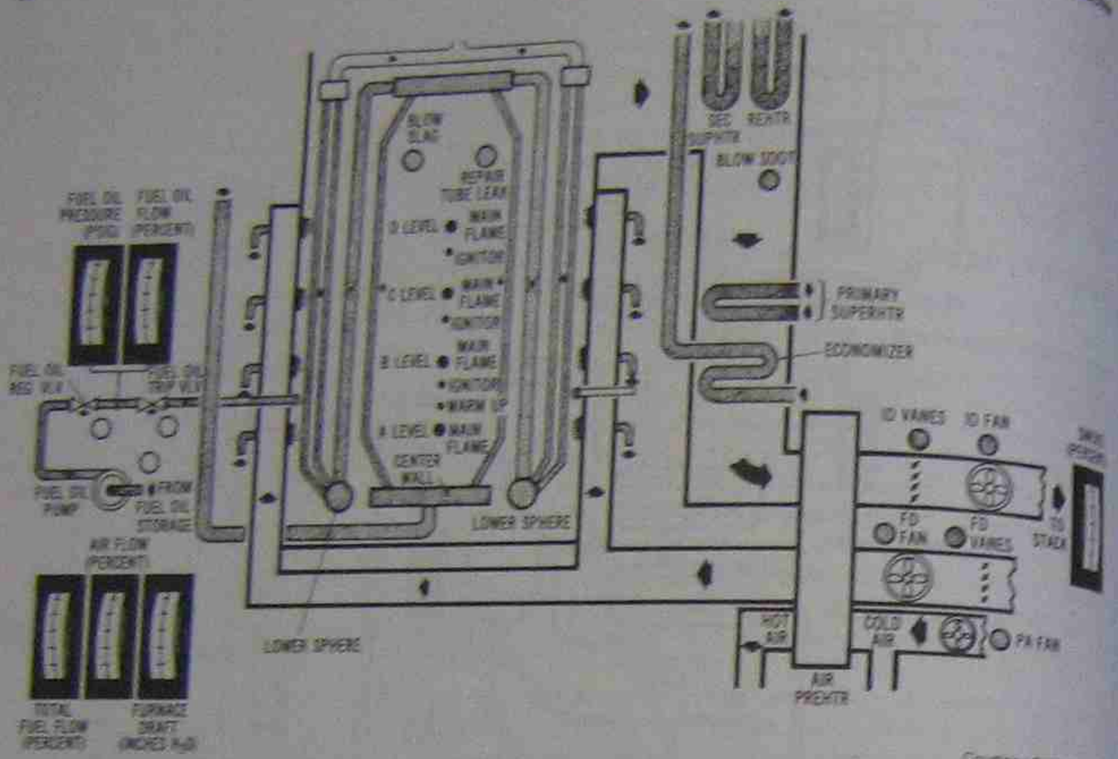
Oil-Fired System Simulator

An oil-fired electrical power system simulator is shown in Fig. 2-15. This system is very similar to the coal-fired system. The subsystems are identical to those used in the coal-fired system except, of course, there is no coal-pulverizing system.

HYDROELECTRIC SYSTEMS

The use of water power goes back to ancient times. It has been developed to a very high degree, but is now taking a secondary role due to the emphasis on other power sources that are being developed in our country today. Electrical power production systems using water power were developed for use in the early 20th Century.

The energy of flowing water may be used to generate electrical power. This method of power production is used in hydroelectric power systems as shown by the simple system illustrated in the diagram of Fig. 2-16. Water, which is confined in a large reservoir, is channeled through a control gate which adjusts the flow rate. The flowing water passes through the blades and control vanes of a hydraulic turbine which produces rotation. This mechanical energy is used to rotate a



Courtesy Combustion, Inc.

Fig. 2-11. The fuel and air subsystem.

generator that is connected directly to the turbine shaft. Rotation of the alternator causes electrical power to be produced. However, hydroelectric systems are limited by the availability of large water supplies. Many hydroelectric systems are part of multipurpose facilities. For instance, a hydroelectric power system may be part of a project planned for flood control, recreation, or irrigation. Some hydroelectric power systems are shown in Figs. 2-17 through 2-19.

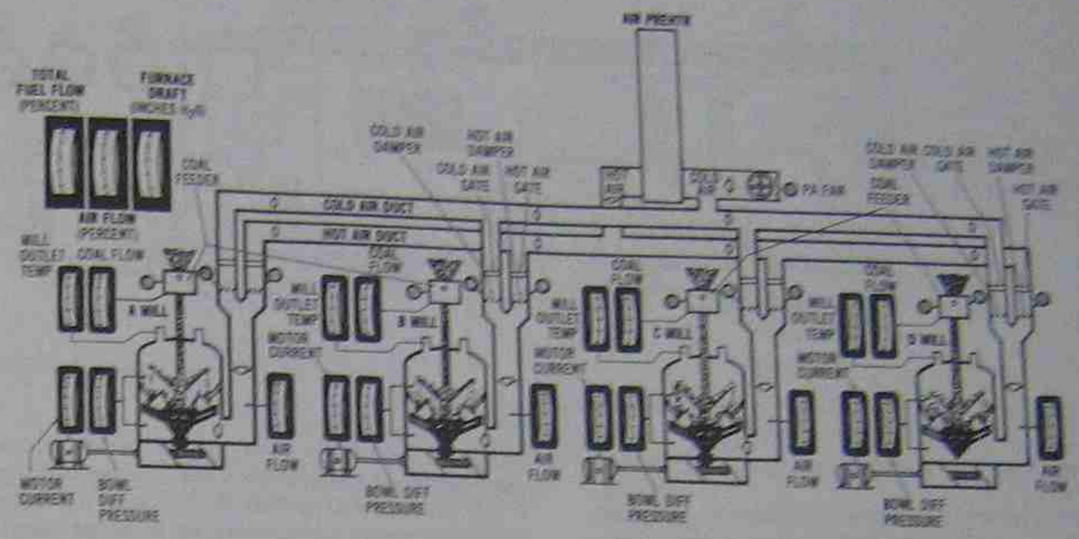
Hydroelectric System Operation

The turbines used as the mechanical-energy sources of hydroelectric systems are very efficient machines. They are ordinarily connected directly to the shaft of a three-phase generator which produces the electrical power. See Figs. 2-2 and 2-20, which show the arrangement of the various parts of a hydroelectric power system.

Water is channeled in from a higher level down into a spiral set of blades on the turbine. The force of water flowing onto these blades causes a rotation of the turbine in the desired direction. The water which flows past the turbine blades is then channeled into a lower-level lake or reservoir area. The angle of the turbine blades can be adjusted to control the speed of rotation of the turbine. Since rotational speed must remain constant to produce a 60-Hz frequency, the blade-angle adjustment and the amount of water channeled onto the blades must be adjusted continuously. Also, varying amounts of force are required to turn the turbine so that different amounts of power are delivered by the turbine to rotate the generator. As the load demand delivered by the generator increases, the power input to the turbine must be increased accordingly. This control is accomplished by adjusting the angle of the blades and the amount of water channeled into the blades. The adjustments are automatically accomplished by servo control systems.

Hydraulic Turbines

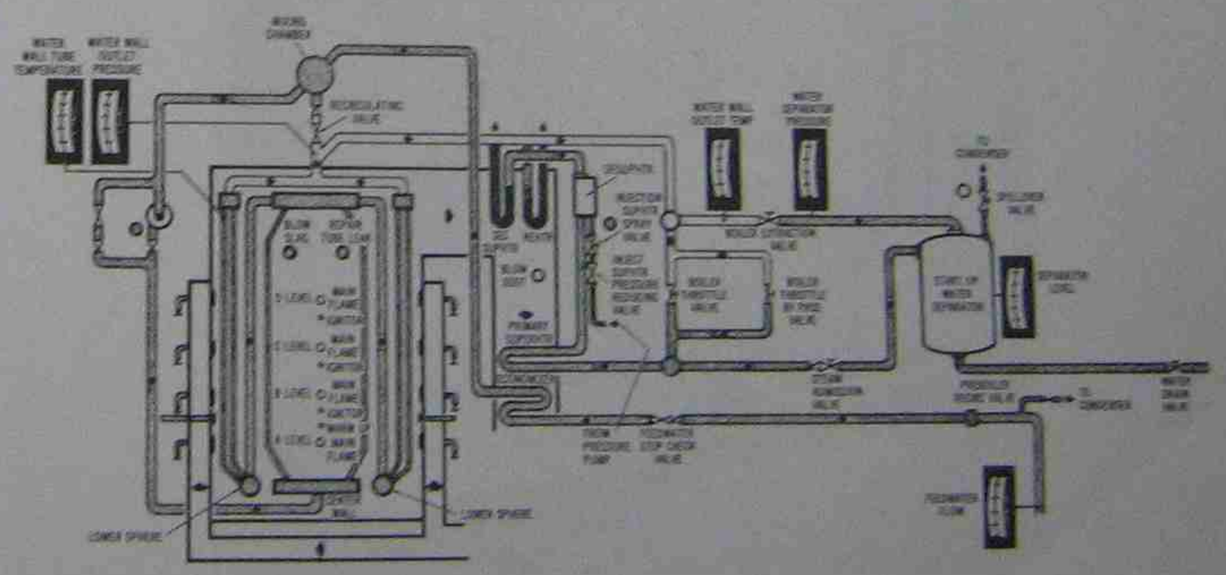
The production of electrical energy by hydroelectric systems is dependent upon the operation of hydraulic turbines. Hydraulic turbines convert the energy produced by the force of moving water into a mechanical energy. This type of turbine is connected to the shaft of a generator at a hydroelectric plant. Some typical generators inside a hydroelectric power plant are shown in Fig. 2-21. Since ac generators at power plants must rotate at a constant speed, the hydraulic turbine must turn at a fixed rate of speed. The efficiency of hydraulic turbines is much greater (in excess of 85%) than most rotating machines.



Courtesy Combustion, Inc.

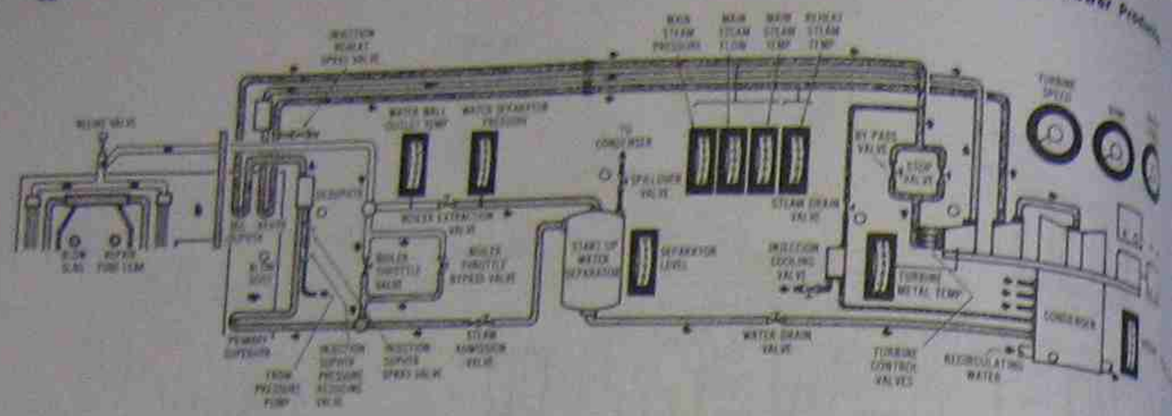
Fig. 2-12. The coal pulverizer subsystem.

The type of hydraulic turbine used with a hydroelectric power system determines whether the generators have horizontal or vertical shafts. Vertical shaft designs are the most common. Electrical power is produced by a three-phase ac generator connected directly to the shaft of the hydraulic turbine. Several hydroelectric systems are used as "reserve" systems for peak load times. They may be put into operation much faster than steam-driven power systems. It is also possible for the generators of a hydroelectric system to be operated as three-phase synchronous motors during low demand periods. The motor can rotate the hydraulic turbine which is then capable of pumping water. Water is pumped so that a higher external water level is achieved. The higher water elevation will then assist in the production of power during peak load intervals.



Courtesy Combustion, Inc.

Fig. 2-13. The boiler-water subsystem.



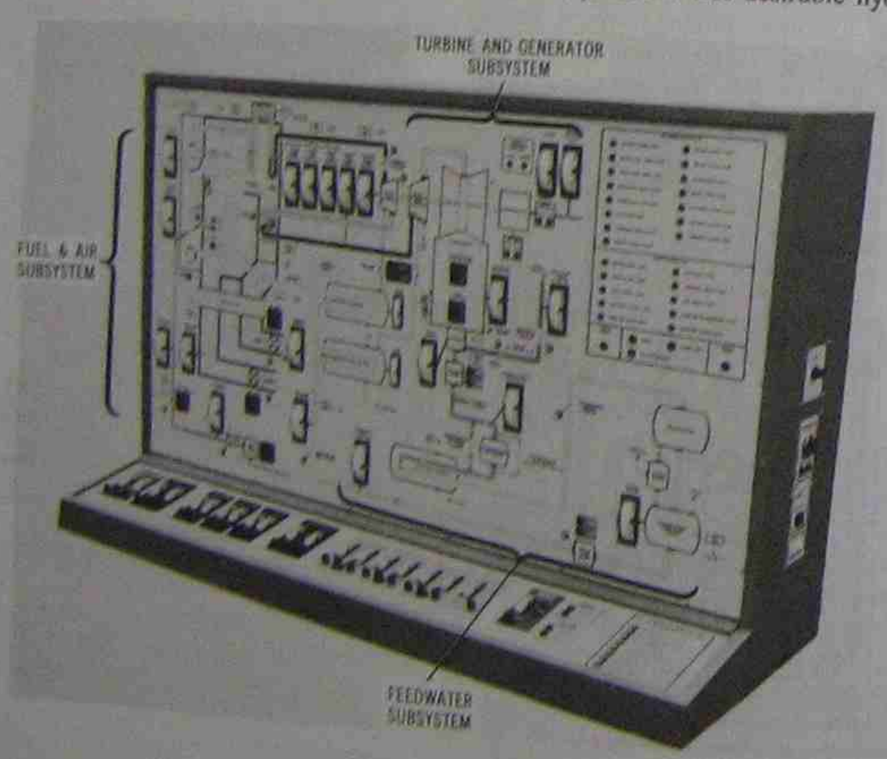
Courtesy Omnidata

Fig. 2-14. The steam and turbine subsystem.

FUTURE OF HYDROELECTRIC SYSTEMS

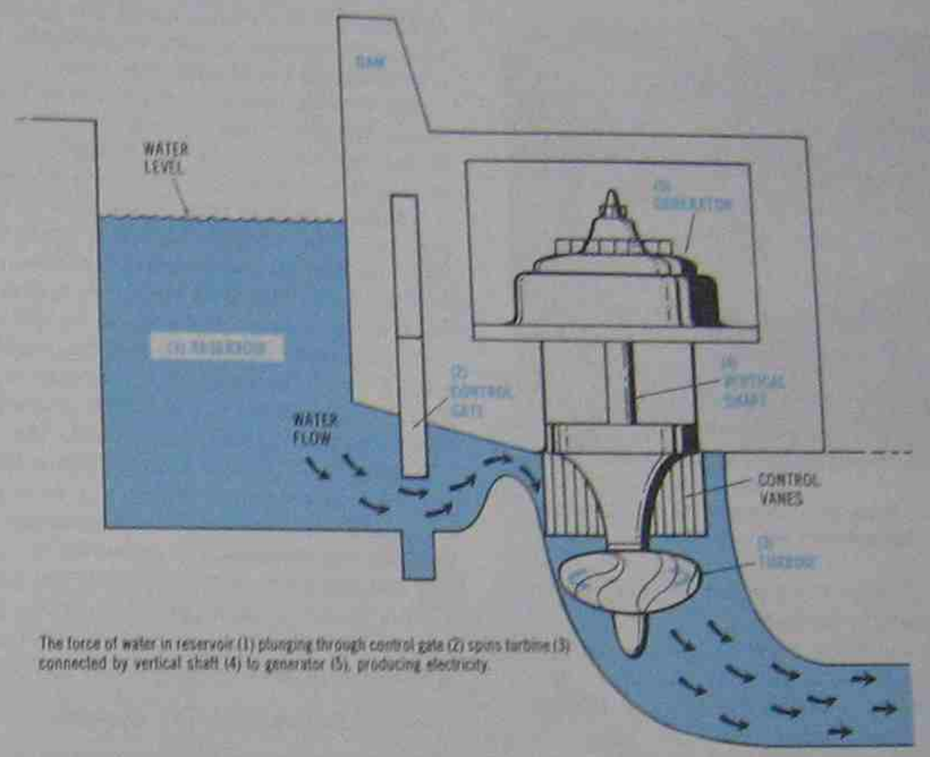
About 10% of the power produced in the United States is produced by hydroelectric power systems. After the initial cost of a hydroelectric generating facility, the electrical power production cost is relatively inexpensive. Hydroelectric systems are easier to start up and stop than are other power production systems in use today. Other advantages of hydroelectric systems are those not associated with the production of electrical power. These benefits, derived from the construction of multipurpose dams, include navigational control of waterways, flood control, irrigation, w development of recreational areas. Another advanta is that hydroelectric systems do not cause a consump tion of the energy source which produces the electric power as do other systems in use today.

Hydroelectric generating projects are considered t be low cost and produce little pollution. However, i the United States, we have already used the most de sirable sites for installing hydroelectric systems. Sinc the cost of developing other alternative power systems such as nuclear and geothermal, has become so grea the development of less desirable hydroelectric sites i



Courtesy Omnidata, Inc.

Fig. 2-15. An oil-fired electrical power system simulator.

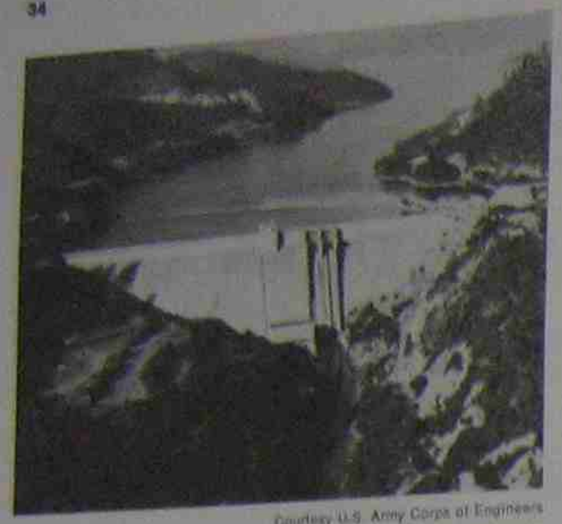


The force of water in reservoir (1) plunging through control gate (2) spins turbine (3) connected by vertical shaft (4) to generator (5), producing electricity.

Fig. 2-16. Drawing of a basic hydroelectric power system.

Courtesy U.S. Army Corps of Engineers

Fig. 2-17. John Day Dam on the Columbia River. (A 2.7 megawatt hydroelectric power plant.)



Courtesy U.S. Army Corps of Engineers

Fig. 2-18. Green Peter Dam, Oregon. (An 80,000 kilowatt hydroelectric power plant.)

now feasible. Future development of hydroelectric power systems may be inevitable.

To motivate our using water to produce electrical power is the fact that if we used this natural resource to its full potential, it would give us other benefits. These were discussed earlier. Although the cost to produce electrical power with hydroelectric systems depends on a number of factors, it is generally considered to be a very cheap source of energy. The costs are primarily dependent upon the location of the power plant. The desirability of the site is dependent upon its natural characteristics, which affect the cost of development and its regional characteristics, which, in turn, affect the market for the power.

In the late 1930s, water supplied about 40% of the electrical power in the United States. Now, however, water power supplies only about 10% of the nation's electrical power. This is due to the massive development of other power production methods. It is estimated that, in the future, water power will account for an even lower percentage of electrical power generation. Despite this projected decrease, hydroelectric plants are still being built, and the hydroelectric capacity of the United States is still substantial. Hydroelectric systems are not now being developed rapidly; however, with our ever-increasing energy problems and the shortages of our other natural resources, water systems may still have a useful potential.

Pumped-Storage Hydroelectric Systems

Over 10,000 megawatts of electrical power is developed in the United States by pumped-storage hydroelectric systems. This type of system, shown in Fig. 2-22, operates by pumping water to a higher elevation and storing it in a reservoir until it is released to drop to a lower elevation to drive the hydraulic turbines in a hydroelectric power-generating plant.

The variable nature of the electrical load demand makes pumped-storage systems desirable to operate. During low-load periods, the hydraulic turbines may be used as pumps to pump water to a storage reservoir of a higher elevation from a water source of a lower elevation. The water in the upper reservoir can be stored for long periods of time, if necessary. When the electrical load demand on the power system increases, the water in the upper reservoir can be allowed to flow (by gravity feed) through the hydraulic turbines which will then rotate the three-phase generators in the power plant. Thus, electrical power can be generated without any appreciable consumption of fuel. The pump-turbine and motor-generator units are constructed so that they will operate in two ways: (1) as a pump and motor, and (2) as a turbine and generator. In either case, the two machines are connected by a common shaft and operate together. However, the multiple use of these machines, although economically a very attractive method, limits the amount of time that a pumped-storage system can generate electrical power.

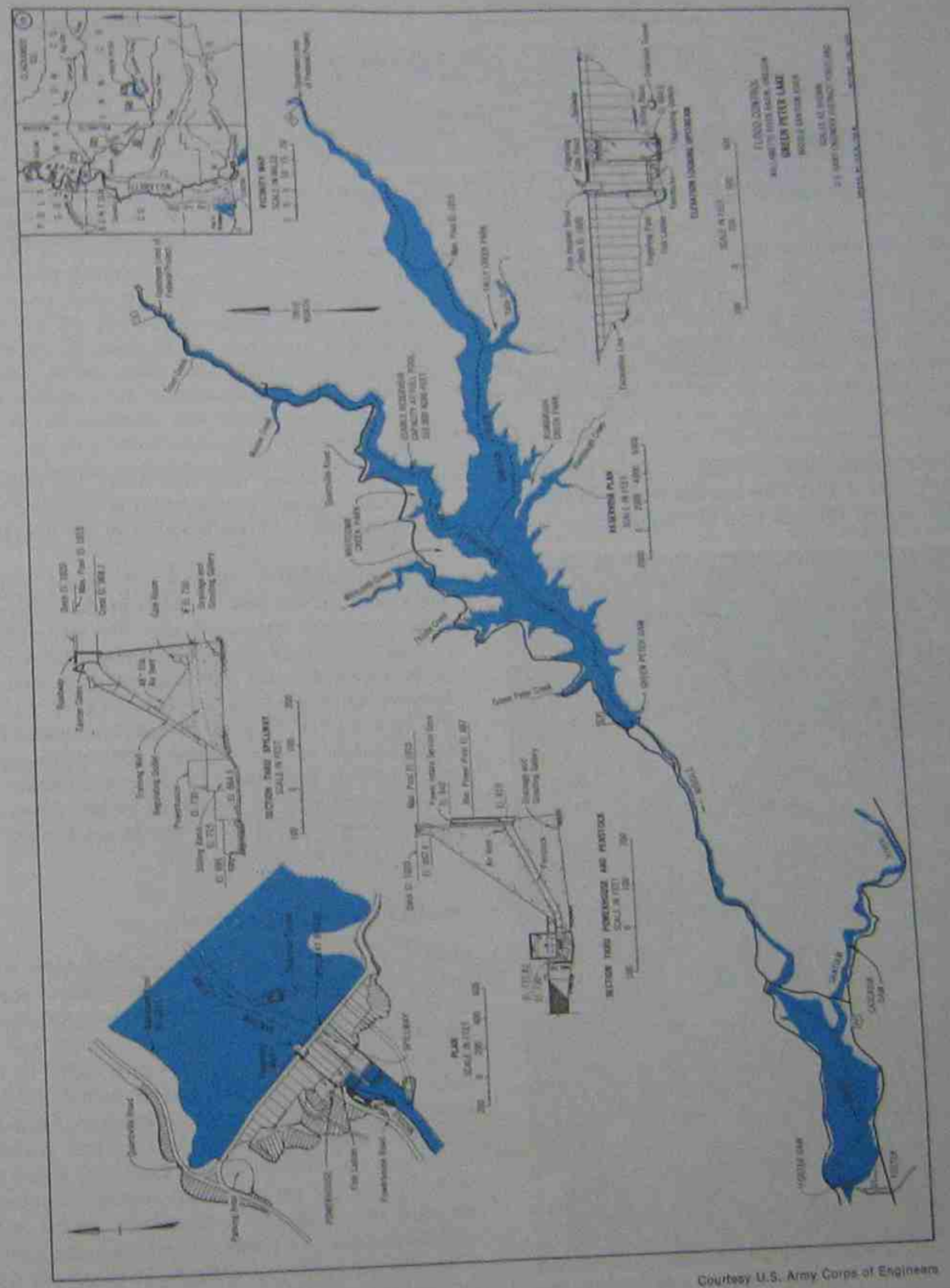
Future of Pumped-Storage Systems

The future of pumped-storage systems depends primarily on economic factors. If fuel and capital construction costs continue to rise, pumped-storage systems might be developed. The conversion of conventional hydroelectric systems to pumped-storage systems has been considered. Also, underground pumped-storage systems have been studied. The underground system would have an upper reservoir at ground level and the lower reservoir underground. The operating principle is the same as in a conventional pumped-storage system.

NUCLEAR-FISSION SYSTEMS

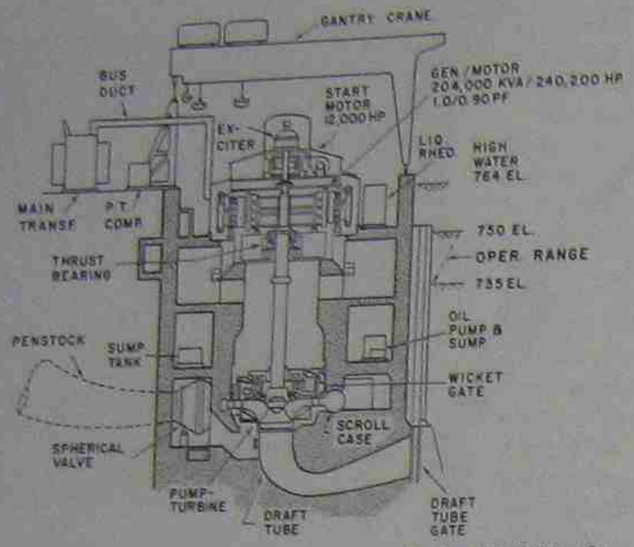
Nuclear power plants in operation today utilize reactors which function due to the nuclear-fission process. Nuclear fission is a complex reaction which results in the division of the nucleus of an atom into two nuclei. This splitting of the atom is brought about by the bombardment of the nucleus with neutrons, gamma rays, or other charged particles and is referred to as induced fission. When an atom is split, it releases a great amount of heat. A nuclear-fission power plant simulator is shown in Fig. 2-23.

In recent years, several nuclear-fission power plants have been put into operation. A nuclear-fission power system, shown in Fig. 2-23, relies upon heat produced during a nuclear reaction process. Nuclear reactors



Courtesy U.S. Army Corps of Engineers

Fig. 2-19. Site layout of the hydroelectric project at Green Peter Lake.



Courtesy Allis-Chalmers Co.

Fig. 2-20. Cutaway drawing of a hydroelectric power station section at a main unit showing equipment arrangement.

"burn" nuclear material whose atoms are split causing the release of heat. This reaction is referred to as nuclear fission. The heat from the fission process is used to change circulating water into steam. The high-pressure steam rotates a turbine which is connected to an electrical generator. This is shown in the diagram of Fig. 2-25.

Courtesy U.S. Army Corps of Engineers

Fig. 2-21. Generators inside a hydroelectric power plant.

The nuclear-fission system is very similar to fossil-fuel systems in that heat is used to produce high-pressure steam which rotates a turbine. The source of heat in the nuclear-fission system is a nuclear reaction while, in the fossil-fuel system, heat is developed by a burning fuel. At the present time, less than 10% of the electrical power produced in the United States comes from nuclear-fission sources. However, this percentage is also subject to rapid change as new power facilities are put into operation. An operational nuclear power system is shown in Fig. 2-26. A typical power plant site layout is given in Fig. 2-27.

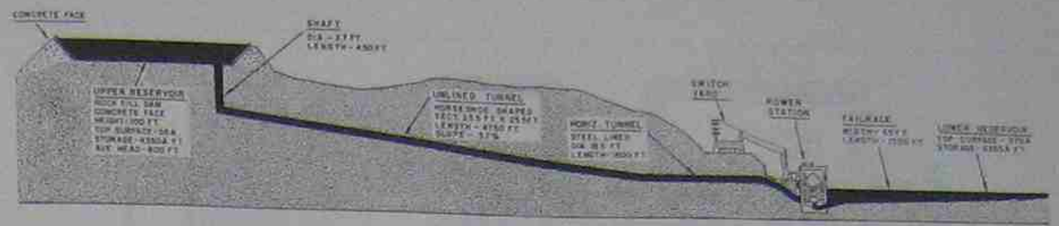
Nuclear Power Fundamentals

In order to better understand the process involved in producing electrical power by nuclear-fission plants, we should review some basic fundamentals. An atom is the smallest particle into which an element can be broken. The central part of an atom is called its nucleus (this is how the term "nuclear power" was derived). The nucleus of an atom is composed of protons which are positively charged particles and neutrons which have no electrical charge. Electrons, which are negatively charged particles, orbit around the nucleus. An atom of any element is electrically neutral in its natural state since the number of protons in the nucleus is equal to the number of electrons which orbit around the nucleus.

The number of protons (+) and electrons (−) contained by an atom varies from one atom to another. (For further information concerning atomic number, mass, etc., refer to the table of Elements given in Appendix B.) The number of neutrons (0) in an atom is not always the same as the number of protons and electrons. Atoms which have additional neutrons are called isotopes. For instance, a hydrogen atom normally has one electron, one proton, and no neutrons. If one neutron is added to this atomic structure, heavy hydrogen or deuterium is formed. Deuterium is an isotope of hydrogen.

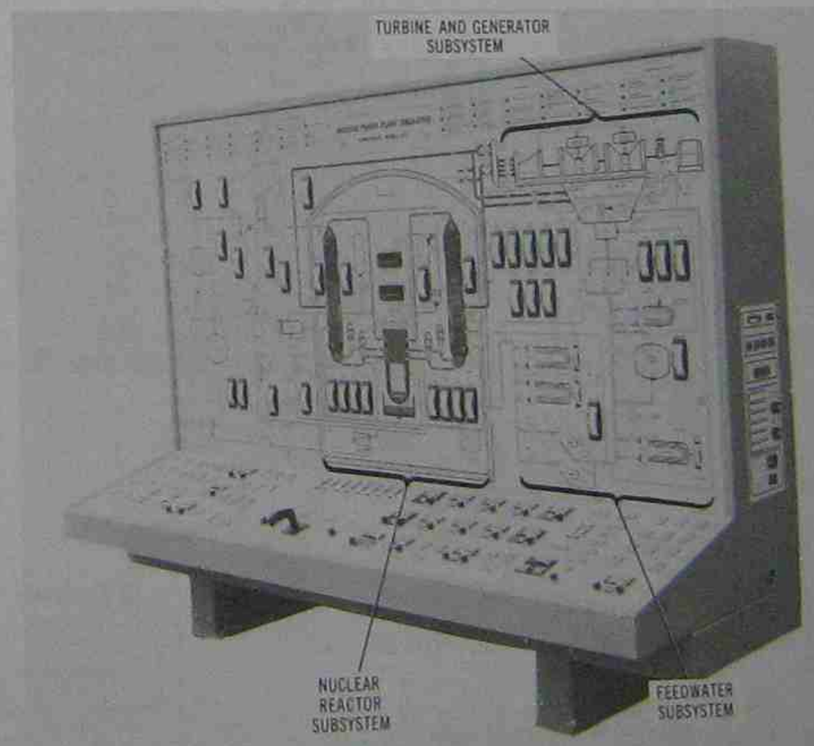
The element uranium has many different isotopes, each of which contains 92 protons. If the isotope has 143 neutrons in the nucleus, uranium-235 is formed. Uranium-235 has proved to be a valuable nuclear fuel, but less than 1% of the uranium metal ore mined is of the uranium-235 type.

The fission or splitting reaction of uranium-235 or other nuclear fuels is an interesting process. It requires separate controlled neutrons, traveling at high velocities, to penetrate the orbiting electrons around the nucleus of the U-235 isotope. Once a high-velocity neutron has struck the nucleus, the nucleus will split into two smaller nuclei. This reaction causes a large quantity of heat to be released. When a nucleus splits, other neutrons from within it are released. These neutrons can cause additional fission reactions in other U-235 isotopes. Thus, the fission reaction occurs as a chain reaction which causes massive amounts of heat energy to be given off.



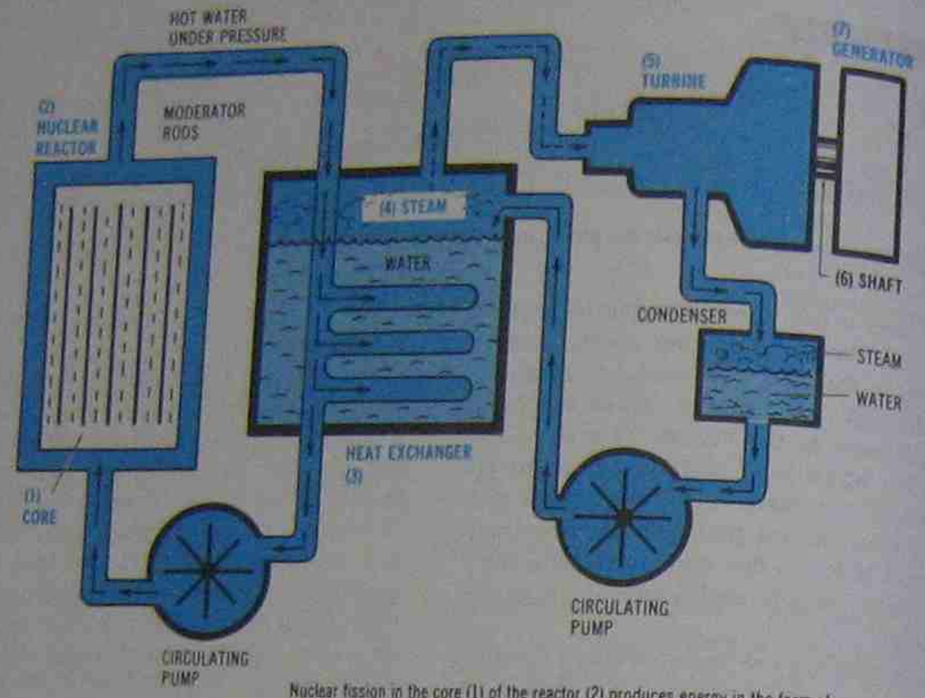
Courtesy Allis-Chalmers Co.

Fig. 2-22. A pumped-storage hydroelectric power plant. (Shown is a diagrammatic section of the Taum Sauk project.)



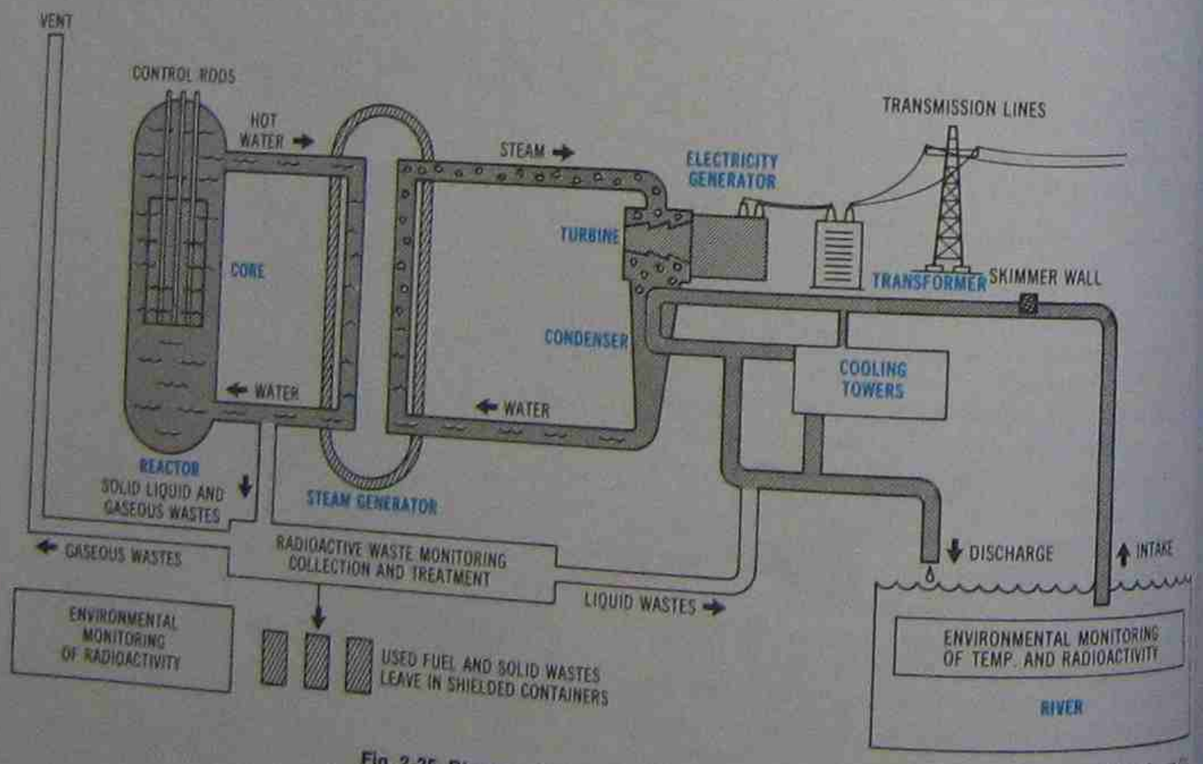
Courtesy Omnidata, Inc.

Fig. 2-23. Nuclear power plant simulator.



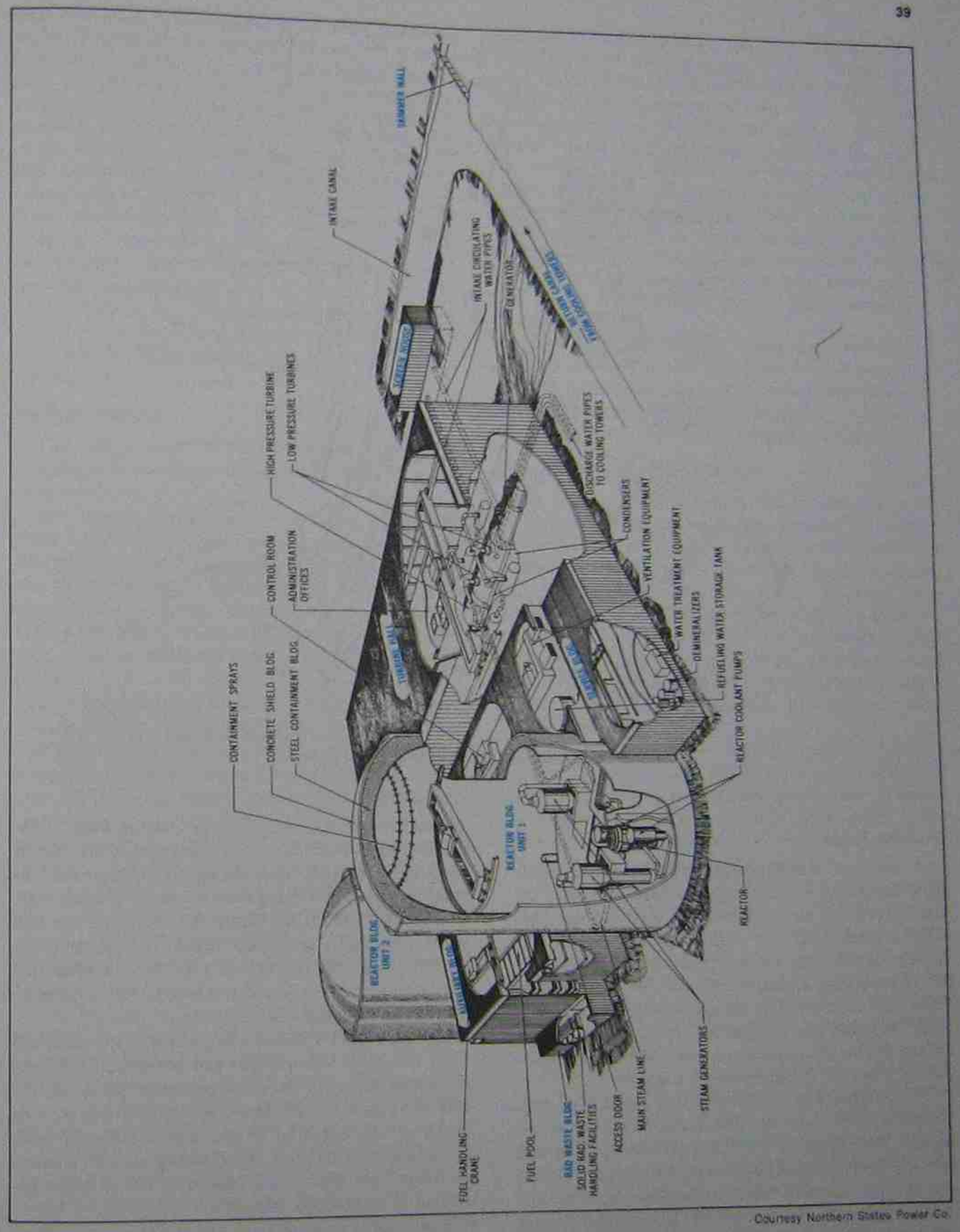
Nuclear fission in the core (1) of the reactor (2) produces energy in the form of heat, which heats water under pressure. The heat from the water in this primary system is transferred to a secondary stream of water in heat exchanger (3) converting it into steam (4), which spins the turbine (5) connected by shaft (6) to generator (7), producing electricity.

Fig. 2-24. Drawing illustrating the principles of a nuclear-fission power system.



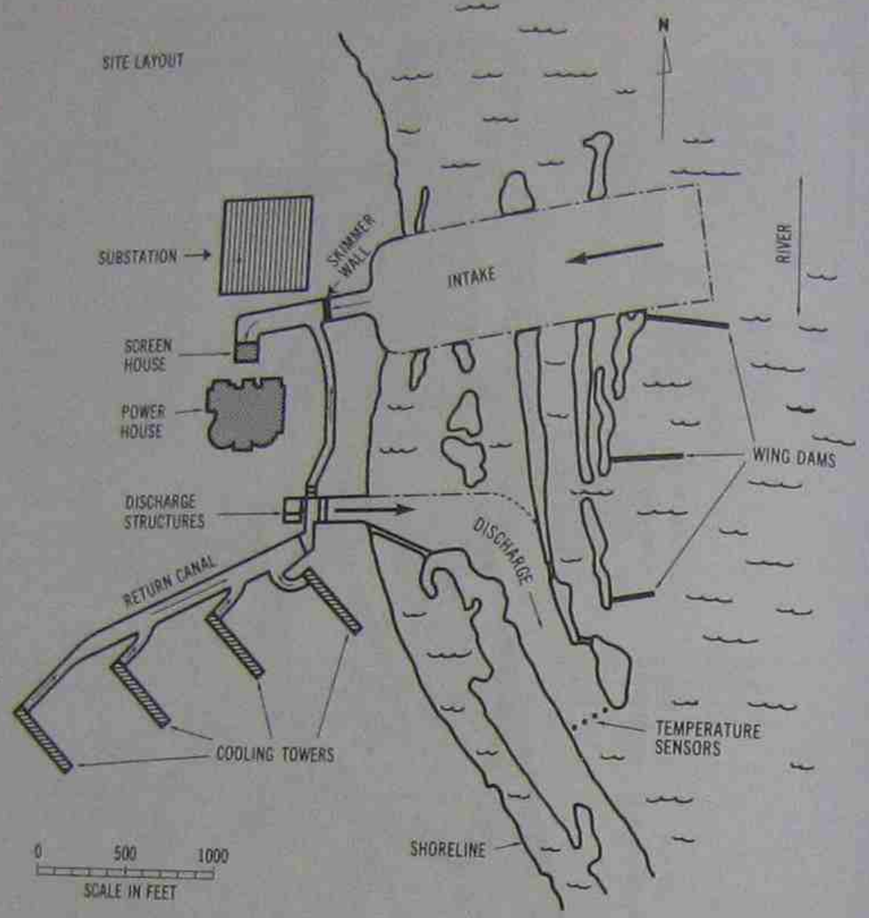
Courtesy Northern States Power C

Fig. 2-25. Diagram of the nuclear reaction process.



Courtesy Northern States Power Co.

Fig. 2-26. An operational nuclear-fission power plant.



Courtesy Northern States Power Co.

Fig. 2-27. Typical site layout of a nuclear power plant.

Nuclear Fuels

A sustained nuclear-fission reaction is dependent upon the use of a proper type of fuel. The most desirable fuels for nuclear-fission reactions are uranium-233, uranium-235, and plutonium-239. These three nuclear materials are the only fissionable isotopes capable of producing sustained reactions. Of these nuclear fuels, the only one that occurs naturally is uranium-235. The other two isotopes are produced by artificial means. Ordinarily, nuclear reactors which use uranium-235 as a fuel are called *converter reactors*.

The possibility of a nuclear-fission reaction producing as much or more fuel than is used has been investigated. Such reactors are called *breeder reactors* and use uranium-233 and plutonium-239 as fuels. During the nuclear reactions which take place in a breeder reactor, materials that are used in the reaction process are converted to fissionable materials. The long-range development of nuclear power production may be dependent upon whether or not breeder reactors can be made available soon. Since the types of nuclear reactors which are presently being used consume uranium-235, it is thought that in the future the supply of this fuel will become low, forcing its price to rise substantially. A price increase in this naturally available nuclear fuel would make nuclear power production less economically competitive with other systems.

Uranium fuel for nuclear-fission reactors is produced from ore and is then purified and converted to the desired state through a series of processes. Most nuclear fuel elements are made into a series of plates or rods which are protected by a cladding of stainless steel, zirconium, or aluminum. The cladding must be capable of withholding the nuclear fuel so as not to allow the release of radioactive materials.

Used fuel is released from the fission reactors when it no longer produces heat effectively during the nu-

clear reaction. It is not depleted at this time; therefore, further processing can bring about the recovery of more fuel from the used fuel. The used fuel, which is released from a nuclear reactor, is usually stored underwater for a period of time to permit cooling and radioactive shielding. This type of storage reduces the radioactivity of the fuel. After the storage period has elapsed, the fuel may be reprocessed more safely and easily. The reprocessing of nuclear fuel is very expensive. A large factor contributing to this cost is the expense of constructing a reprocessing facility. These facilities must be extensively shielded for radiation protection, both internally and externally. The production and use of nuclear fuels in the United States is rigidly controlled. An agency of the federal government keeps a continuous account of all nuclear fuels produced, used, or reprocessed.

Nuclear Reactors

There are a variety of types of nuclear reactors. The major type used in the United States has been the water-moderated reactor.

The fundamental difference between a nuclear power plant and a conventional power plant is the fuel that is employed. Most conventional power plants burn coal, oil, or gas to create heat while the present nuclear plants "burn" uranium. Burning uranium has proved to be a very effective source of power production; however, there is much controversy over this source of power.

It is estimated that burning one ounce of uranium has roughly the same energy output as the burning of 100 tons of coal. The "burning" which takes place in a nuclear reactor is referred to as nuclear fission. Nuclear fission is the method used in nuclear power generation and it is quite different from ordinary combustion. The burning of coal results from the carbon combining with oxygen to form carbon dioxide, along with the release of heat. The fissioning or splitting of the uranium atom results in the uranium combining with a neutron and, subsequently, splitting into lighter elements. This process produces a massive quantity of heat.

The reactors used at nuclear power plants must be capable of controlling fission reactions. When nuclear fuels are bombarded by neutrons, they split and release energy, radiation, and other neutrons. This process is a sustained chain reaction, producing a great amount of heat energy, which is used for the production of steam, which is used to rotate a steam turbine-generator system. The nuclear-fission power-generating system is about the same as a conventional fossil-fuel steam plant, except a nuclear reactor is used to produce the heat energy rather than a burning fuel confined in a furnace.

Within the nuclear reactor, there is a mixture of fuel and a moderator material. There are three known nuclear-fission fuels—uranium-235, uranium-233, and plutonium-239. Moderators are used to slow the speed of fission neutrons. Since the neutrons involved in the fission reaction have high energy levels, they are called fast neutrons. They are slowed by collisions with moderator materials such as water, deuterium oxide, beryllium, and other lightweight materials. Neutrons which have been slowed down possess an energy equilibrium and are referred to as thermal neutrons. These thermal neutrons aid additional fission reactions. Thus, moderators play a significant role in sustaining nuclear-fission reactions.

Nuclear reactors differ in several ways. Differences include the type of fuel and moderator, the thermal output capacity, and the type of coolant. Several classifications of nuclear reactors, according to types of coolant, are discussed in the following sections.

Moderating Nuclear Reactors

A uranium atom undergoes fission when it absorbs a neutron and, at the same time, produces two lighter elements and emits two or three neutrons. These neutrons, in turn, react with other uranium atoms, which will undergo fission and produce more neutrons. Heat is increased in the reactor as the number of neutrons is increased. If a reactor is left uncontrolled, it may destroy itself. Moderating a reactor, therefore, means controlling the multiplication of neutrons in the reactor core. There are several methods used for moderating nuclear reactors.

Boiling-Water Reactor (BWR)—Water is a popular coolant for reactors. In this type of reactor, shown in Fig. 2-28, water is pumped into the reactor enclosure. The water is then converted into steam which is delivered to a steam turbine. The water also serves as the moderator material of the reactor.

Pressurized-Water Reactor (PWR)—The pressurized-water reactor, shown in Fig. 2-29, is similar to a boiling-water reactor except that the coolant water is pumped through the reactor under high pressure. Steam is produced in an adjacent area from a separate stream of water which is pumped through the steam-production system. Just as in the BWR, the water within the reactor serves as the moderator.

High-Temperature Gas-Cooled Reactor (HTGR)—The high-temperature gas-cooled reactor, shown in Fig. 2-30, uses pressurized helium gas to transfer heat from the reactor to a steam-production system. The advantage of helium gas over water is that the helium can operate at much higher temperatures.

Other Types—Other types of reactors, such as the liquid-metal fast-breeder reactor (LMFBR) and the

molten-salt cooled reactor, have some potential in electrical power production systems. The LMFBR type is shown in Fig. 2-31.

OPERATIONAL ASPECTS OF MODERN POWER SYSTEMS

There are several operational aspects of modern electrical power production systems which must be considered. These considerations include the location of power plants, electrical load requirements, and electrical load demand control. Each of these will be discussed in the following sections.

Location of Electrical Power Plants

A critical issue which now faces those involved in the production of electrical power is the location of power plants. New federal regulations associated with the National Environmental Policy Act (NEPA) have made the location of power plants more difficult. At present, there is a vast number of individual power plants throughout the country. However, the addition of new generating plants involves such current issues as air pollution, water pollution, materials handling (particularly with nuclear plants), fuel availability and federal, state, and municipal regulations.

These issues have brought about some recent thought about the construction of "energy centers." Such systems would be larger and more standardized than the power plants of today. This concept would reduce the number of plants that are needed to produce a specific quantity of electrical power. Other advantages of the concept include better use of land resources, easier environmental control management, and a more economic construction and management of facilities. These advantages may make centralized power production the best alternative, socially, economically, and technically, for meeting future electrical power requirements.

Electrical Load Requirements

The electrical power which must be produced by our power systems varies greatly according to several factors such as the time of the year, the time of the week, and the time of the day. Electrical power supply and demand is much more difficult to predict than most quantities that are bought and sold. Electrical power must be readily available and in sufficient quantity whenever it is required. The overall supply and demand problem is something most of us take for granted until our electrical power is interrupted. Electrical power systems in the United States must be interconnected on a regional basis so that power stations can support one another in meeting the variable load demands.

The use of electrical power is forecasted to increase every ten years at a rate that will cause a doubling of the kilowatt hours required. Some forecasts, however, show the rate of electrical power demand to have a

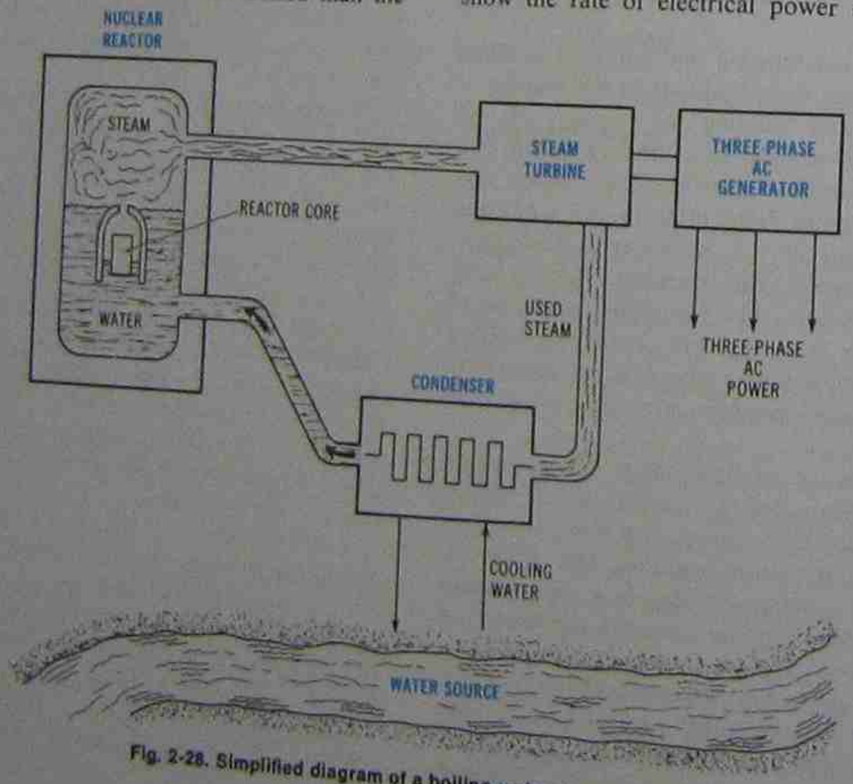


Fig. 2-28. Simplified diagram of a boiling-water reactor (BWR).

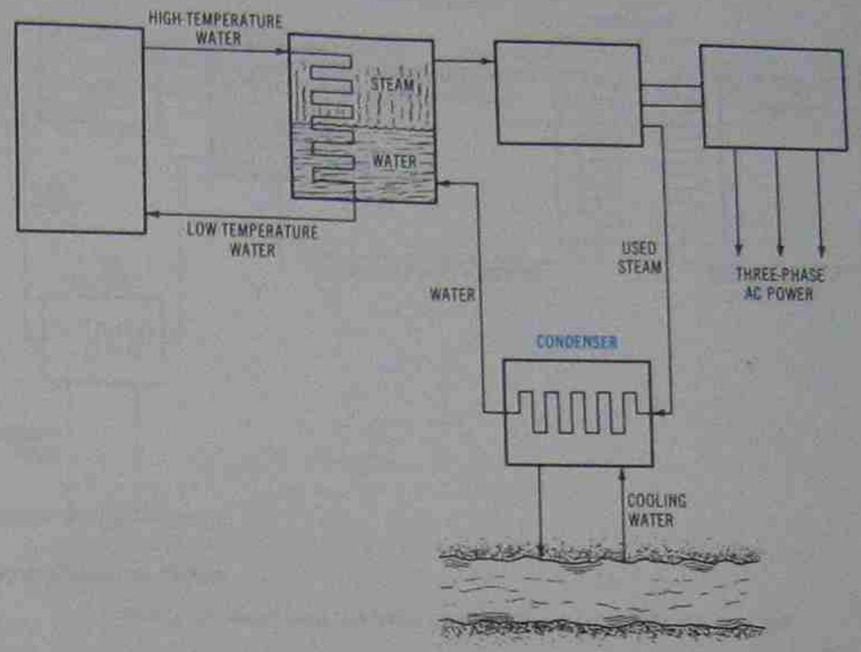


Fig. 2-29. Simplified diagram of a pressurized-water reactor (PWR).

"leveling-off" period in the near future. This effect may be due to a saturation of the possible uses of electrical power for home appliances, industrial processes, and commercial use. These factors, combined with greater conservation efforts, and social and economic factors, support the idea that the electrical power demand will increase at a lesser rate in future years. The forecasting of the present demand by the electrical utilities companies must be based on an analysis by regions. The demand varies according to the type of consumer that is supplied by the power stations (which comprise the system). A different type of load is encountered

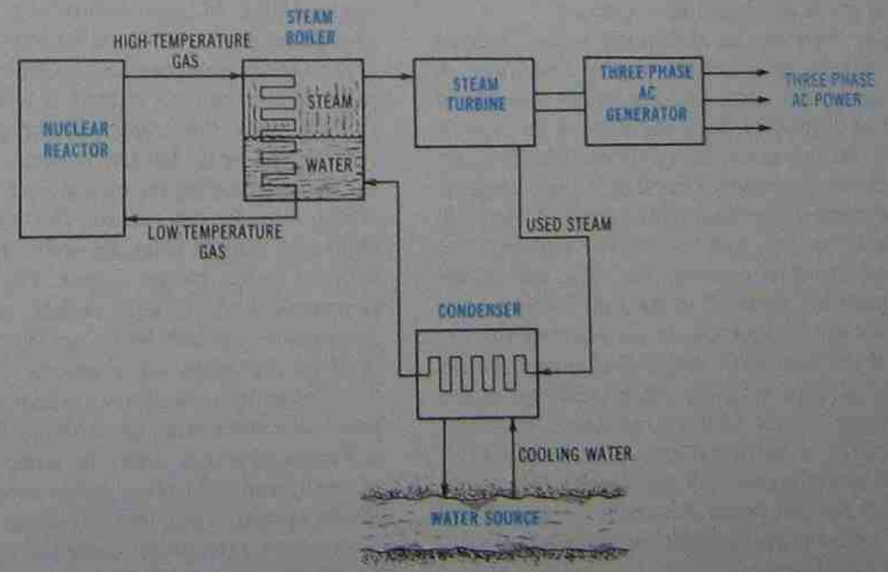


Fig. 2-30. Simplified diagram of a high-temperature gas-cooled reactor (HTGR).

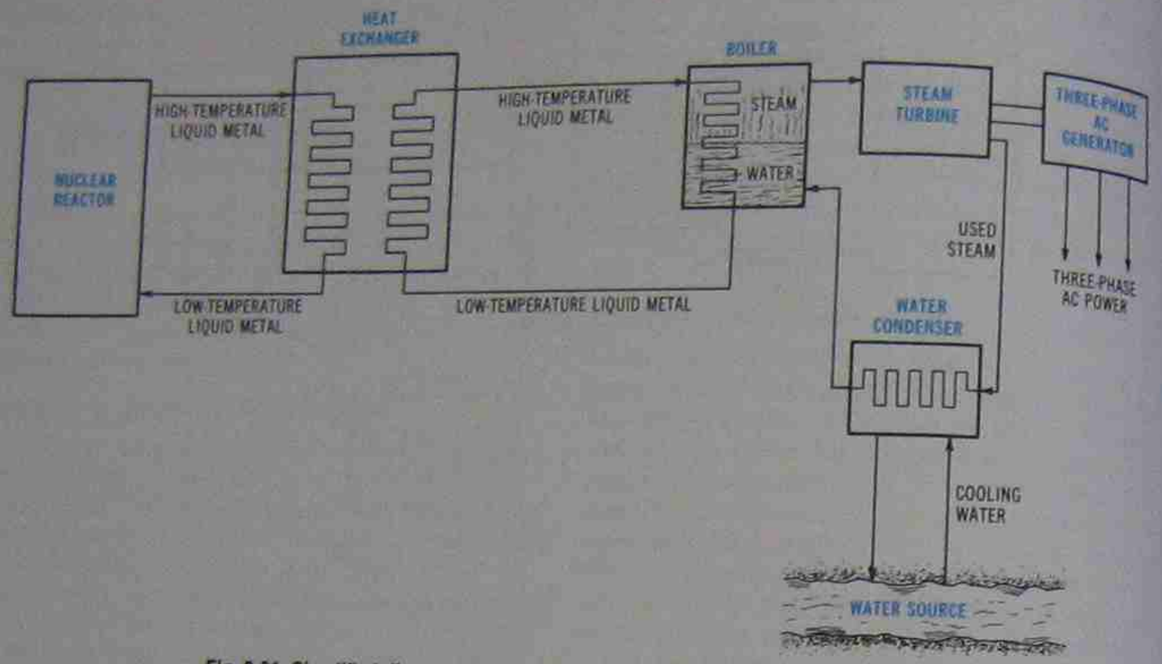


Fig. 2-31. Simplified diagram of the liquid-metal fast-breeder reactor (LMFBR).

when residential, industrial, and commercial systems are supplied by the utilities companies.

Industrial use of electrical power accounts for over 40% of the total kilowatt-hour (kWh) consumption and the industrial use of electrical power is projected to increase at a rate similar to its present rate in the near future. The shortage of natural gas should not significantly affect electrical power consumption by industry. Most of the conversions of gas systems will be to the usage of oil systems in their place.

The major increases in residential power demand have been due to an increased use by customers. A smaller increase was accounted for by an increase in the number of customers. Such variables as the type of heating used, the use or nonuse of air conditioning, and the use of major appliances (freezers, dryers, ranges), affect the residential electrical power demand. At present, residential use of electrical power accounts for over 30% of the total consumption. The rate of increase will probably taper off in the near future.

Commercial use of electrical power accounts for less than 25% of the total kWh usage. Commercial power consumption includes usage by office buildings, apartment complexes, school facilities, shopping establishments, and motel or hotel buildings. The prediction of the electrical power demand by these facilities is somewhat similar to the residential demand. Commercial use of electrical power is also expected to increase at a declining rate in the future.

Electrical Load-Demand Control

As the costs of producing power continue to rise, power companies must search for ways to limit the maximum rate of energy consumption. To cut down on power usage, industries have begun to initiate programs which will cut down on the load during peak operating periods. The use of certain machines may be limited while other large power-consuming machines are operating. In larger industrial plants and at power-production plants, it would be impossible to manually control the complex regional switching systems, so computers are being used to control loads.

To prepare the computers for power-consumption control, the peak demand patterns of local industries and the surrounding region supplied by a specific power station must be determined. The load of an industrial plant may then be balanced according to area demands with the power station output. The computer may be programmed to act as a switch, allowing only those processes to operate which are within the load calculated for the plant for a specific time period. If the load drawn by an industry exceeds the limit, the computer may deactivate part of the system. When demand is decreased in one area, the computer can cause the power system to increase power output to another part of the system. Thus, the industrial load is constantly monitored by the power company to insure a sufficient supply of power at all times.

PROBLEMS

1. The average load for a power plant during a 12-hour period is 500 megawatts. The peak load for the same time period is 620 megawatts. The output capacity of the power plant is 780 megawatts. Calculate:
   a. The load factor of the plant.
   b. Capacity factor.
2. Calculate the load factor and capacity factor of a power plant which has the following output characteristics—an average load (24 hours) of 210 megawatts, a peak load of 290 megawatts, and a plant capacity of 300 megawatts.

CHAPTER 3

Alternative Power Systems

Several methods of producing electrical power are either in limited use or in the experimental stage at the present time. Some of these methods show promise as a possible electrical power production method for the future.

POTENTIAL POWER SOURCES

Solar power is one potential electrical power source. The largest energy source available today is the sun which supplies practically limitless energy. The energy available from the sun far exceeds any foreseeable future need. Solar cells are now being used to convert light energy into small quantities of electrical energy. Possible solar-energy systems might include home heating or power production systems, orbiting space systems, and steam-driven electrical power systems. Each of these systems utilizes solar collectors that concentrate the light of the sun so that a large quantity of heat will be produced. Potentially, this heat could be used to drive a steam turbine in order to generate additional electrical energy.

Geothermal systems also have promise as future energy sources. These systems utilize the heat of molten masses of material in the interior of the earth. Thus, heat from the earth is a potential source of energy for power generation in many parts of the world. The principle of geothermal systems is similar to other steam turbine-driven systems. However, in this case, the source of steam is the heat obtained from within the earth through wells. These wells are drilled to a depth of up to two miles into the earth. Geothermal sources are used to produce electrical energy in certain regions of the western United States.

Wind systems have also been considered for producing electrical energy. However, winds are variable in most parts of our country. This fact causes wind systems to be confined to being used with storage systems, such as batteries. It is possible that wind machines may be used to rotate small generators which could, potentially, be located at a home. However, large amounts of power would be difficult to produce by this method.

Another energy source which has some potential for future use is magnetohydrodynamics (MHD). The operation of an MHD system relies upon the flow of a conductive gas through a magnetic field, thus causing a direct-current voltage to be generated. The electrical power developed depends upon the strength of the magnetic field which surrounds the conductive gas and on the speed and conductivity of the gas. At the present time, only small quantities of electrical energy have been generated using the MHD principle; however, it does have some potential as a future source of electrical energy.

Still another possible energy source is nuclear fusion. This process has not been fully developed due to the extremely high temperatures which are produced as fusion of atoms takes place. A fusion reactor could use tritium or deuterium (heavy hydrogen) as fuels. These fuels may be found in sea water in large quantities, thus reducing the scarcity of nuclear fuel. It is estimated that there is enough deuterium in the oceans to supply all the energy the world would ever need.

If nuclear-fusion reactors could be used in the production of electrical energy, the process would be similar to the nuclear-fission plants which are now in operation. The only difference would be in the nuclear reaction which takes place to change the circulating water into steam to drive the turbines. The major problem of the nuclear-fusion process is in controlling the high temperatures generated. These are estimated to reach 100 million degrees Fahrenheit.

Another energy source which could be used in the future is the fuel cell. This type of cell converts the chemical energy of fuels into direct-current electrical energy. A fuel cell contains two porous electrodes and an electrolyte. One type of fuel cell operates as hydrogen gas passes through one porous electrode and oxygen gas passes through the other electrode. The chemical reactions of the electrodes with the electrolyte

either release electrons to an external circuit or draw electrons from the external circuit, thus producing a current flow.

Still another possible alternative power production system utilizes tidal energy. Tidal systems would use the rise and fall of the water along a coastal area as a source of energy for producing electrical power. Coal gasification is yet another process which could be used for future power systems. This process is used to convert the poorer grades of coal into a gas. The use of oil shale to produce fuel is also being considered.

It should be pointed out that many of the future energy sources are direct-conversion processes. For example, the fuel cell converts chemical energy directly to electrical energy and the solar cell converts light energy directly to electrical energy. A more complex transformation of energy takes place in most power plants today. Heat energy is needed to produce mechanical energy which produces electrical energy. This explains the inefficiency of our present systems of producing electrical energy. Perhaps advances in electrical power technology will bring about new and more efficient methods of producing electrical energy.

SOLAR ENERGY SYSTEMS

For many years, many have regarded the sun as a possible source of electrical power. However, few efforts to use this cheap source of energy have been made. We are now faced with the problem of finding alternative sources of energy and solar energy is one possible alternative source. The sun delivers a constant stream of radiant energy. The amount of solar energy coming toward the earth through sunlight in one day equals the energy produced by burning many millions of tons of coal. It is estimated that enough solar energy is delivered to the United States in less than one hour to meet the power needs of the country for one year. This is why solar energy is a potential source for our ever-growing electrical power needs. However, there are still several problems to be solved prior to using solar energy. One major problem is in developing methods for controlling and utilizing the energy of the sun. There are two methods for collecting and concentrating solar energy presently in use. Both of these methods involve a mirror-like reflective surface.

The first method uses parabolic mirrors to capture the energy of the sun. These mirrors concentrate the energy from the sun by focusing the light onto an opaque receiving surface. If water could be made to circulate through tubes, the heat focused onto the tubes could turn the water into steam. The steam, then, could drive a turbine to produce mechanical energy.

The mirrors could be rotated to keep them in proper position for the best light reflection.

The second method uses a flat-plate solar collector. Layers of glass are laid over a blackened metal plate with an air space between each layer. The layers of glass act as a heat trap. They let the rays of the sun in but keep most of the heat from escaping. The heated air could be used to warm a home.

The first widespread use of solar energy will probably be to heat homes and other buildings. Experiments in doing this are already underway in many areas. To heat a home, a flat-plate collector may be mounted on the part of the roof that slopes in a southward direction. It should be tilted at an angle to receive the greatest amount of sunlight possible. The sun would be used to heat a liquid (or air) which would be circulated through the collector. The heated liquid (air) would be stored in an insulated tank and, then, pumped into the

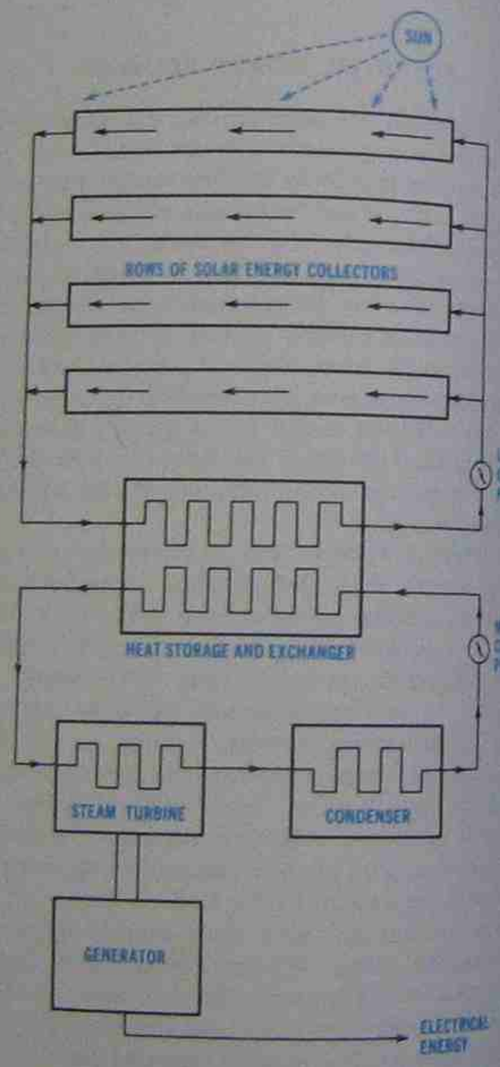


Fig. 3-1. Block diagram of a solar power system.

house through pipes and radiators (air ducts). The system could be as shown in the top portion of Fig. 3-1. By adding a steam turbine, a generator, etc., to the solar collector just discussed, the heat could be used to drive the steam turbine to generate electrical energy. This solar power system is illustrated in Fig. 3-1.

Another major problem in solar heating is in the storage of the heat produced by the sun. In areas that have several cloudy days each year, an auxiliary heating system is required. However, solar energy is being used today on a limited basis. For instance, flashlights and radios can be powered by solar cells. The main advantage of this usage is that a solar battery can be used for an infinite period of time. Considering all of these aspects of solar energy and its potential, many feel that solar energy will be the next major form of energy to be utilized extensively in the United States. The development of large-scale power production systems which use solar energy, however, remains questionable.

GEOTHERMAL POWER SYSTEMS

About 20 miles below the crust of the earth is a molten mass of liquid and gaseous matter called magma, which is still cooling from the time that the earth was formed. When this magma comes close to the crust of the earth, possibly through a rupture, a volcano could be formed and erupt. Magma could also cause steam vents, like the ones at the "Geysers" area in California. These are naturally occurring vents which permit the escape of the steam that is formed by the water which comes in contact with the underground magma. A basic geothermal power system is shown in Fig. 3-2 and the understructure for such a system is illustrated in Fig. 3-3.

In the 1920s, an attempt was made to use the Geysers area as a power source, but the pipelines were not able to withstand the corrosive action of the steam and the impurities in it. Later, in the 1950s, stainless steel alloys were developed that could withstand the steam and its impurities, so the Pacific Gas and Electric Company started development of a power system to use the heat from within the earth as an energy source. The first generating unit at the Geysers power plant began operation in 1960. At present, over 500 megawatts of electrical power is available from the generating units in the Geysers area. The Geysers geothermal power plant is shown in Figs. 3-4 and 3-5.

In the geothermal system, steam enters a path (through a pipeline or a vent) to the surface of the earth. The pipelines which carry the steam are constructed with large expansion loops that cause small pieces of rock to be left in the loop. This system of loops avoids damage to the steam turbine blades. Some of the expansion loops in the pipes which carry the steam are shown in Fig. 3-6. After the steam goes through the turbine, it goes to a condenser, where it is combined with cooler water. This water is pumped to cooling towers where the water temperature is reduced. This part of the geothermal system is similar to conventional steam systems.

The geothermal power production method offers another alternative method of producing electrical

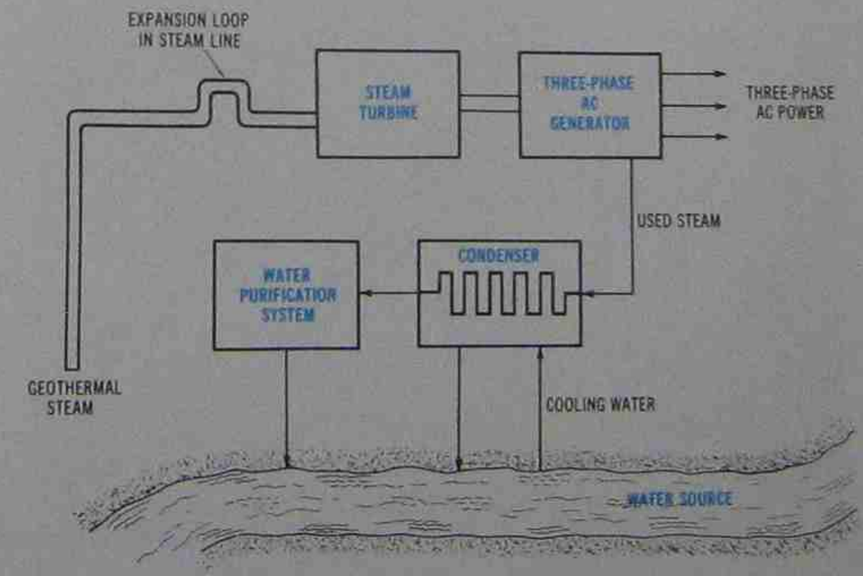
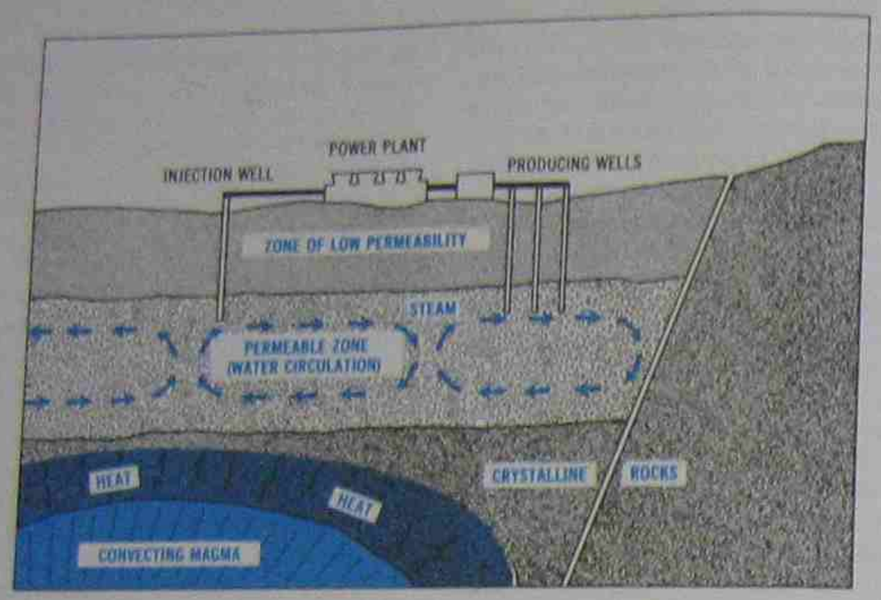


Fig. 3-2. Drawing of a basic geothermal power system.



Courtesy Pacific Gas and Electric Co.

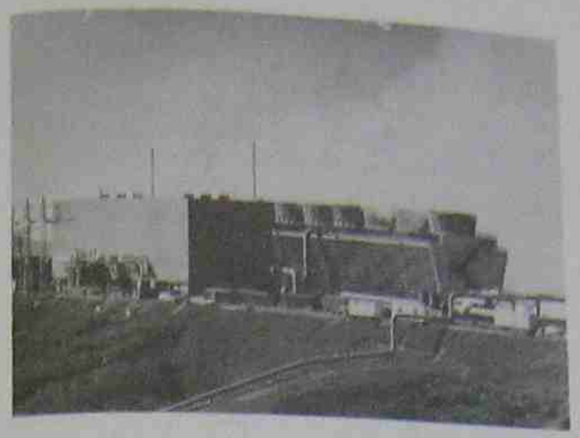
Fig. 3-3. Drawing of a basic geothermal power system that illustrates the underground structure.

ower. This method makes it possible to control energy, the form of steam or heated water, that is produced natural geysers or underground channels. The high- essure steam for power production is made without rning any of our fossil fuels. Thus, this method can be used to drive turbine-generator systems, such as the one at the Geysers system in California.

The setting up of a geothermal power plant requires the drilling of holes deep into the surface of the earth. One hole may be used to send cold water down into

Courtesy Pacific Gas and Electric Co.

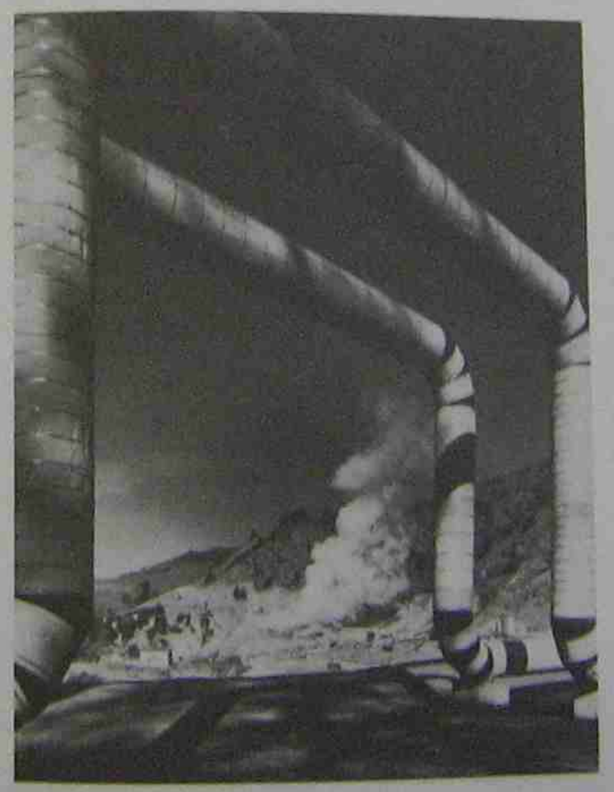
Fig. 3-4. An operational geothermal power system.



Courtesy Pacific Gas and Electric Co.

Fig. 3-5. The Geysers geothermal power plant.

the tremendously hot material located under the surface of the earth. An adjacently drilled hole could be used to bring steam back to the surface. This method is capable of being used in any area of the world but it requires drilling holes up to 10 miles deep. On the other hand, natural geothermal steam production is limited to active volcanic areas such as the Geysers area of the United States. Since no fuel is burned, geothermal methods represent one way of saving our valuable and diminishing quantities of fossil fuels. The major problem associated with geothermal power production is the drilling of the deep holes into the ground.



Courtesy Pacific Gas and Electric Co.

Fig. 3-6. Steam expansion loops of a geothermal system.

WIND SYSTEMS

Nonpolluting, inexpensive power systems have been desired for many years. Now, technology has advanced to the point where there may be some inexpensive methods of producing electrical power that we have not used significantly before.

In the early 1900s, in many farm areas, particularly in the Midwest, electrical power had not been distributed to homes. It was conceived that the wind could be used to provide a mechanical energy not only for water pumps but also for generators with which to provide electrical power. The major problem was that the wind did not blow all the time and, then, when it did, it often blew so hard that it destroyed the windmill. Most of these units used fixed-pitch propellers as fans. They also used low-voltage direct-current electrical systems and there was no way of storing power during periods of nonuse or during times of low wind speeds. These early units used a rotating-armature system (see Chapter 4) and, therefore, along with other maintenance problems, had to have the brushes replaced very often.

The wind generating plants used today have a system of storage batteries, rectifiers, and other components that provides a constant power output even when the wind is not blowing. They also have a 2-blade or 3-blade propeller system that can be "feathered" during periods of high winds so that the mill will not destroy itself. A simplified wind-power system is shown in Fig. 3-7. Most of the systems that are in use today are individual units capable of producing 120-volt alternating current with constant power outputs in the low-kilowatt range. The generator output may be interconnected through a system of series-connected batteries with an automatic, solid-state voltage control that is designed to convert the dc voltage to 120-volt ac. The cost of these individual electrical power-generating systems is fairly low and these systems provide a complete self-contained, nonpolluting, power source. Wind systems would be ideal for remote homes that have a low-power requirement. They should prove to be very dependable and have low maintenance costs. Larger power-generating plants could be possible when located in very windy places. These plants would probably be limited in their power output due to the requirement for large storage batteries. Because of the varying wind speeds, it would be difficult to connect

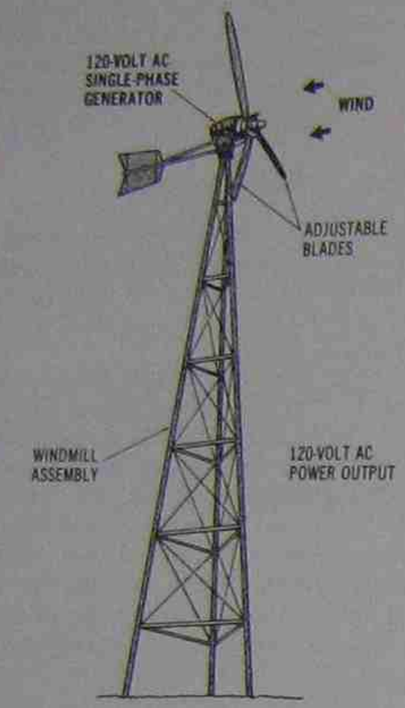


Fig. 3-7. A simplified wind power system.

two or more units in parallel and keep them in a phase relationship. Compared with other inexpensive types of power production plants, such as solar or hydroelectric, wind systems are smaller in physical size per kilowatt output and have a lower initial cast. Also, a solar power plant can only produce power during the daylight hours while a wind generator will operate whenever there is a wind.

The primary disadvantage of a windmill is obvious. What do you do on days without wind? One answer is the use of storage batteries. Another disadvantage is the fact that windmills generally have a very low efficiency—about 50%. Although windmill power will probably never be a large contributor to the solving of any power crisis, some individuals have calculated that several large-diameter windmills, with a fairly constant wind, could produce many kilowatts of electrical power. They could play an important role in reducing the use of our natural resources for electrical power production, particularly on an individual basis.

MAGNETOHYDRODYNAMIC (MHD) SYSTEMS

MHD stands for magnetohydrodynamic, a process of generating electricity by moving a conductor of small particles suspended in a superheated gas through a

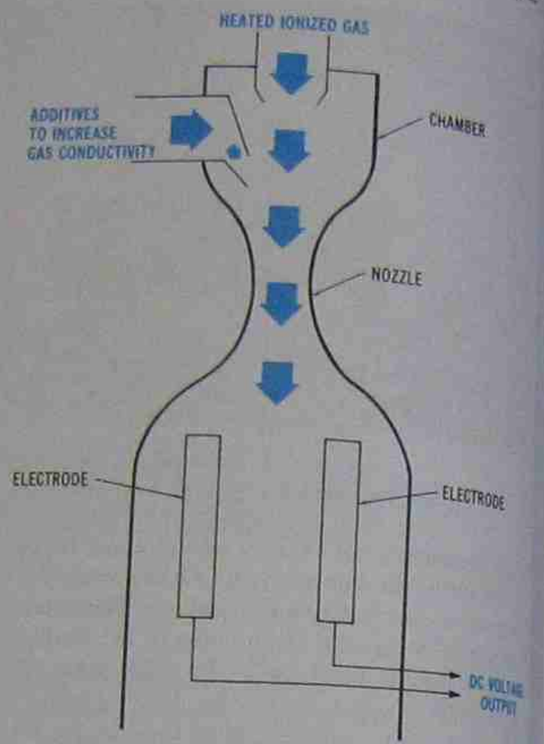


Fig. 3-8. Simplified drawing of a magnetohydrodynamic (MHD) generator system.

magnetic field. The process is illustrated in Fig. 3-8. The metallic conductors are made of metals such as potassium or cesium and can be recovered and used again. The gas is heated to a temperature much hotter than the temperature to which steam is heated in conventional power plants. This superheated gas is in what is called a plasma state at these high temperatures. This means that the electrons of many of the gas atoms have been stripped away, thus making the gas a good electrical conductor. The combination of metal and gas is forced through an electrode-lined channel which is under the influence of a superconducting magnet that has a tremendous field strength. The magnet must be of the superconducting type since a regular electromagnet of that strength would require too much power. A superconducting magnet, therefore, is one of the key parts to this type of generation system.

With high operating temperatures and a high-speed gas flow, it becomes a difficult task to keep the conductive channel from becoming destroyed. Cooling is very important and is accomplished by circulating a suitable coolant throughout jackets built into the channel. Also due to the high temperatures and the metal particles moving at high speed, erosion of the channel becomes a critical problem. This problem has been eased by using a coal slag injected into the hot

gas and metal stream. The coal slag acts to replace the eroded material as it is lost.

Pollution problems are very few. However, the main one is the high levels of nitrogen oxides that are produced. These oxides are the direct result of the high combustion temperatures inherent to the system. Sulfur oxides and ash are also a problem for any plants using coal or oil. An afterburner system has been proposed to eliminate the nitrogen oxides while the sulfur oxides and the ash would be collected, separated chemically and, then, recycled.

At this time, MHD generators are primarily experimental. There have been several large units made, but they have not operated for any significant time periods. Efficiency is of importance for this type of generation system. While the conventional steam generation system (fired by coal) is at most 40% efficient (that is, it turns 40% of the coal energy into electricity) and most nuclear-powered plants are about 33% efficient, MHD plants could operate at 60% efficiency. Thus, fuel supplies could be enhanced by using this generation system. At present, the future of MHD systems for large-scale electrical power generation is questionable.

NUCLEAR-FUSION POWER SYSTEMS

Another alternative power production method which has been considered is nuclear fusion. Deuterium, the type of fuel used for this process, is very abundant. The supply of deuterium is considered to be unlimited since it exists as heavy hydrogen in sea water. The use of such an abundant fuel, however, could solve some of our problems that are related to the depletion of fossil fuels. Another outstanding advantage of this system is that its radioactive waste products would be minimal.

The fusion process results when two atomic nuclei collide under controlled conditions to cause a rearrangement of their inner structure and, thus, release a large amount of energy during the reaction. These nuclear reactions or fusing of atoms must take place under tremendously high temperatures. The energy released through nuclear fusion would be thousands of times greater per unit than the energy from typical chemical reactions and considerably greater than that of a nuclear-fission reaction.

The fusion reaction involves the fusing together of two light elements to form a heavier element, with heat energy being released during the reaction. This reaction could occur when a deuterium ion and a tritium ion are fused together. A deuterium ion is a hydrogen atom with one additional neutron and a tritium ion is a hydrogen atom with two additional neutrons. A temperature in the range of 100,000,000° C is needed for this reaction to produce a great enough velocity for the two ions to fuse together. Sufficient velocity is needed to overcome the forces associated with the ions. The deuterium-tritium-fusion reaction produces a helium atom and a neutron. The neutron, with a high enough energy level, could cause another deuterium-tritium reaction of nearby ions, providing the time of the original reaction is long enough. A much higher amount of energy would be produced by a nuclear-fusion reaction than by a fission reaction. There are several different techniques being investigated for producing nuclear fusion. At this time, each is still in the theoretical development stage.

NUCLEAR-FUSION METHODS

Several methods are being considered today for using the heat from nuclear fusion to generate electrical power.

Magnetic-Confinement Method

One method is called magnetic confinement. The proposed design of a magnetic-confinement power system is shown in Fig. 3-9. At present, it is thought that fusion reactors could be economical if the reaction can be carried out in an intense magnetic field provided by superconducting magnets. The magnet and the magnetic-field designs are very complex, however, and the forces associated with them are tremendous. One such design is shown in Fig. 3-10. Controlling the fusion reaction is still one of the major problems of trying to use this method; therefore, it remains to be studied further.

Laser-Induced Fusion

Laser-induced fusion should also be mentioned. This method relies on inertia rather than an intense magnetic field for the confinement of the nuclear fuel. In this method, a small pellet of frozen fuel is injected into a combustion chamber. There, it is hit by several short, intense, laser beams coming into the chamber from several directions. This process happens very quickly and causes the pellet to collapse due to the intensity of the beams. The fuel is rapidly heated. The fusion reaction takes place at an instant just before the material in the pellet can overcome its inertia and expand due to the intense heating effect. This process uses a laser beam to produce a sufficient amount of heat to cause the nuclear-fusion reaction. A proposed design for a laser-induced fusion power system is shown in Fig. 3-11. As with other fusion methods, this method has not been tested. It is being theoretically developed. However, since the magnetic-confinement method has not been

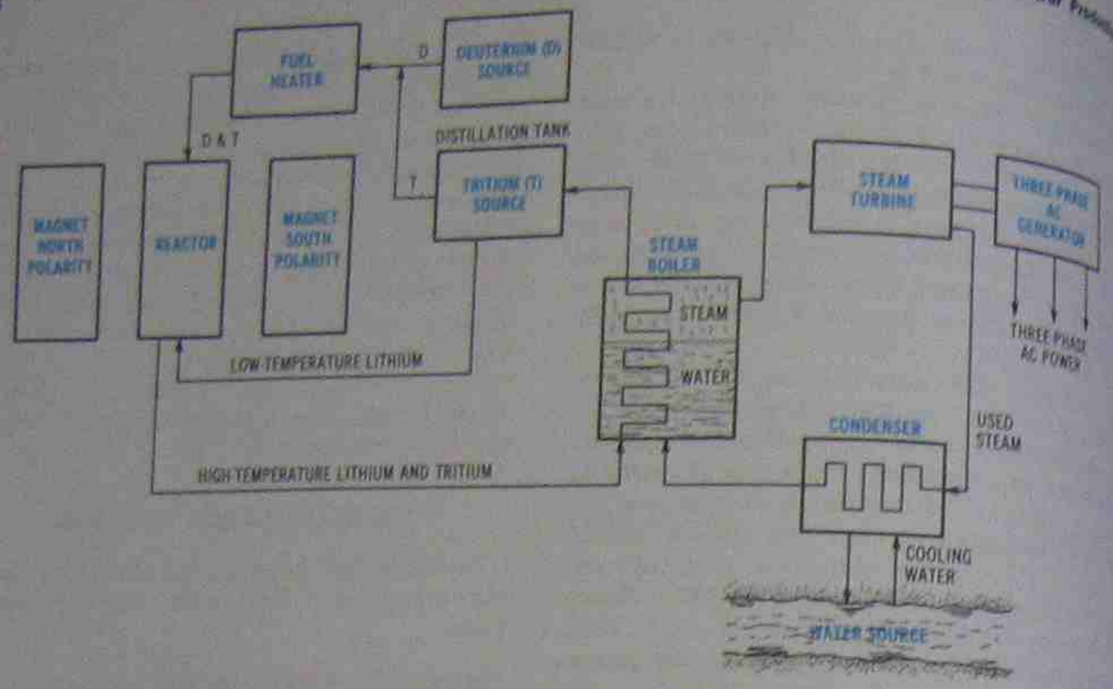
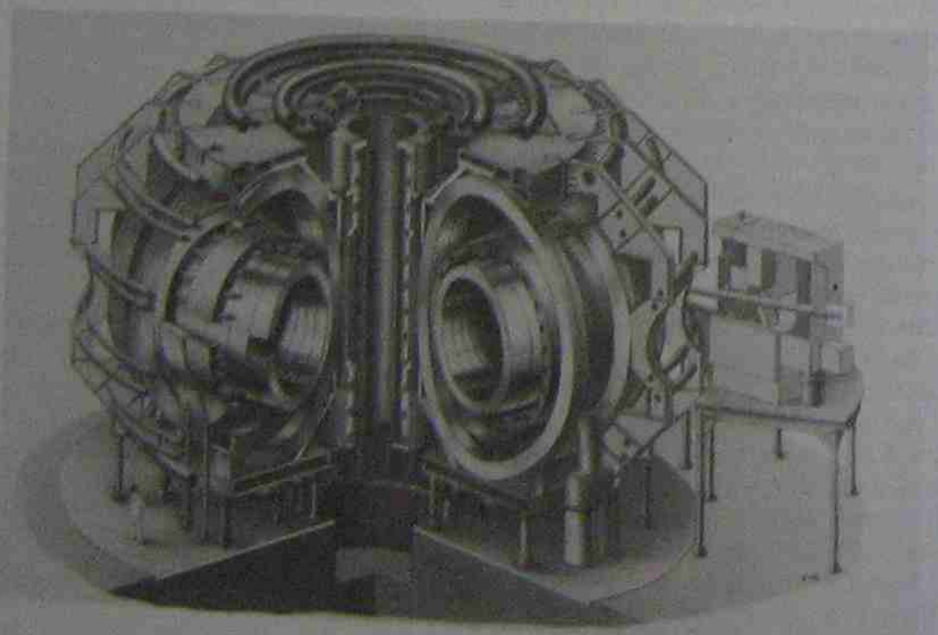


Fig. 3-9. Proposed design of a magnetic-confinement nuclear-fusion power system.

developed beyond the conceptual stage, other methods, such as the laser-induced method, must be considered. It is thought that the pulsed-laser technique may be a viable alternative method for producing sustained nuclear-fusion reactions. This process is presently being developed with deuterium being considered as the proposed fuel.

FUTURE OF NUCLEAR FUSION

Since nuclear fusion is considered to be environmentally safe and would use a very abundant fuel, most research is being done to formulate ways of controlling the fusion-reaction process. Fusion reactors have not yet been developed beyond the theoretical stages. The



Courtesy Oak Ridge National Laboratory

Fig. 3-10. A magnetic-confinement design.

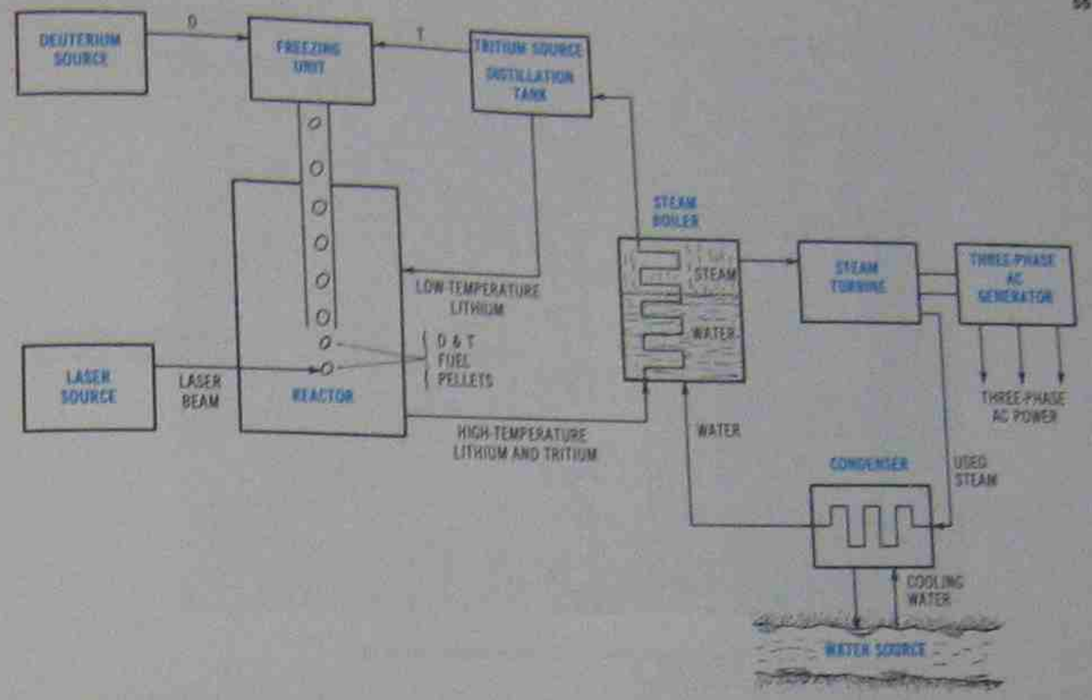


Fig. 3-11. Proposed design of a laser-induced nuclear-fusion power system.

problems involved in constructing a fusion reactor center around the vast amounts of heat produced. The fusion fuel must be heated to a high temperature and, then, the heated fuel must be confined for a long enough period of time that the energy released by the fusion process can become greater than the energy that was required to heat the fuel to its reaction temperature. This is necessary in order to sustain the fusion reaction and to produce continuous energy.

All present fusion power-plant designs have basic problems. Solutions to these problems and development of economically attractive commercial systems will take many years and much money. However, it seems possible that such systems may someday be developed.

FUEL-CELL SYSTEMS

Another alternative energy system which has been researched is the fuel cell. Fuel cells convert the chemical energy of fuels into electrical energy. An advantage of this method is that its efficiency is greater than steam turbine-driven production systems, since the conversion of energy is directly from chemical to electrical. Ordinarily, fuel cells use oxygen and hydrogen gas as fuels, as shown in Fig. 3-12. Instead of consuming its electrodes, as ordinary batteries do, a fuel cell is supplied with chemical reactants from an external source. Ordinarily, hydrogen gas is delivered to the anode of the cell and oxygen gas or air is delivered to the cathode. The reaction of these gases is similar to the reverse of electrolysis. (During the electrolysis process, an electric current decomposes water into hydrogen and oxygen.)

Fuel cells were developed long ago. It was known early that electrochemical reactions could be used to convert chemical energy directly to electrical energy. The first commercial fuel cells were used as auxiliary power sources for United States space vehicles. These were hydrogen-oxygen fuel cells. The development of fuel cells has brought about some cells with a power capacity of up to 500 watts. Some cells that are in the research stages have a power output of up to 100 kilowatts. These fuel cells produce low-voltage direct current. Several cells may be connected in series-parallel configurations to produce greater voltage and current levels. Several large companies are performing experiments with the design of fuel cells. Many new technological approaches to fuel cells are being developed. Large-scale systems are planned for the 1980s which may use phosphoric acid as an electrolyte. This system will operate with a variety of hydrocarbon fuels. Cells presently being developed use high-temperature carbon or alkaline electrolytes. Cells in the developmental stages might use synthetic fuels derived from coal.

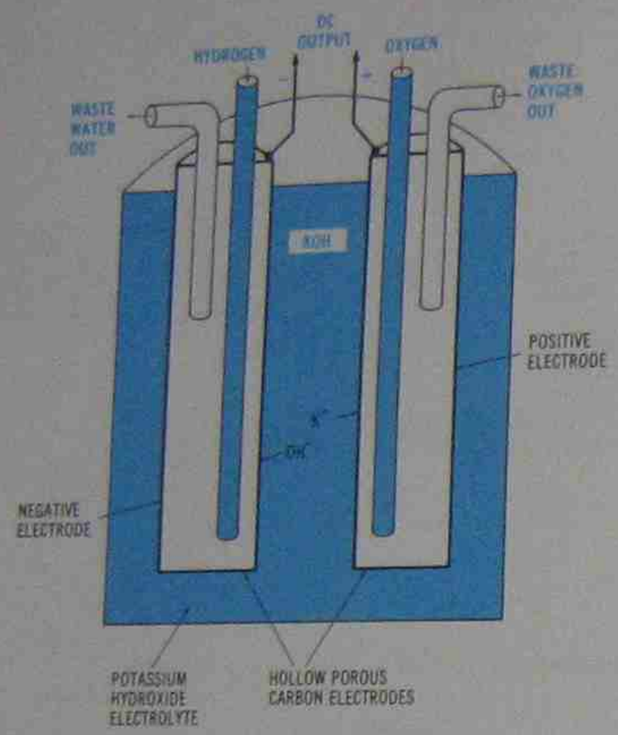


Fig. 3-12. Simplified drawing of a oxygen-hydrogen fuel cell.

Some problems have been encountered in the development of fuel cells. The chemical reaction brought about by the fuels requires a catalyst. The importance of the catalyst is greater at lower operating temperatures. At higher temperatures, cheaper and more abundant catalysts may be used. However, some designers speculate that the catalysts required for lower temperature operation may become unavailable or, if not, at least very expensive in the future. At present, the initial cost of a fuel-cell system is very great. A system, at this time, would not be competitive with other power systems in operation. Another developmental problem is that of water disposal. A vast amount of water is produced by the chemical reactions of the fuels.

Besides space applications, other applications could potentially include mobile electrical power sources. It has been suggested that fuel cells could be used as power sources to drive electric cars. Also, fuel cells are being considered as power sources for trains, submarines, and military vehicles. However, the use of fuel cells for large-scale power systems would not be feasible.

TIDAL POWER SYSTEMS

The rise and fall of waters along coastal areas that is caused by gravitational forces is the basis for the tidal electrical power production method. There are presently some tidal power systems in operation. Tidal systems would be desirable since they do not pollute the atmosphere, do not consume any natural resources, and do not drastically change the surrounding environment as some conventional hydroelectric systems do.

The depth of tidal water varies greatly at different times of the year. These depths are determined by changes in the sun and moon in relation to the earth. Tides are readily predictable since the same patterns are established year after year. A tidal power system would have to be constructed where water in sufficient quantity could be stored with a minimum amount of dam construction. A tidal system could be made to operate during the rise of tides and the fall of tides. Also, the pumped-storage method could be used in conjunction with tidal systems to assure power output during peak load times. A potential tidal system site along the United States-Canada border has been studied; however, the economic feasibility of tidal systems at this time is not too promising. One tidal system that is in operation is at Normandy, France.

COAL-GASIFICATION FUEL SYSTEMS

The process of coal gasification has aroused interest in recent years. This process involves the conversion of coal or coke to a gaseous state through a reaction with air, oxygen, carbon dioxide, or steam. Many

Courtesy Offshore Power Systems

Fig. 3-13. Proposed layout of a floating nuclear plant.

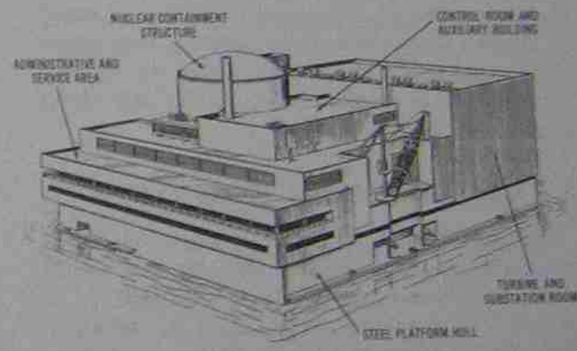
people feel that this process will be able to produce a natural gas substitute. Some of the methods of producing gas from coal include:

1. The BI-GAS process in which a reaction of coal, steam, and hydrogen gas produces methane gas.
2. The COGAS process in which a liquid fuel and a gaseous fuel are produced.
3. The CSG process (or consolidated synthetic gas process) which develops a very slow reaction to produce methane.
4. The Hydrane process in which methane is produced by a direct reaction of hydrogen and coal, with no intermediate gas production.
5. The Synthane process in which methane is produced by a method involving several different steps.

Coal gasification may be one solution to the problem of our depleting natural gas supply. Since some electrical power systems use natural gas as the fuel, we should be concerned about coal gasification as an alternative method to aid in the production of electrical power.

OIL-SHALE FUEL-PRODUCTION SYSTEMS

Another method which should be mentioned as an alternative method that could aid in the production of electrical energy is fuel from oil shale. There is a potential fuel source located at the oil-shale deposits which exist primarily in Colorado, Wyoming, and Utah.

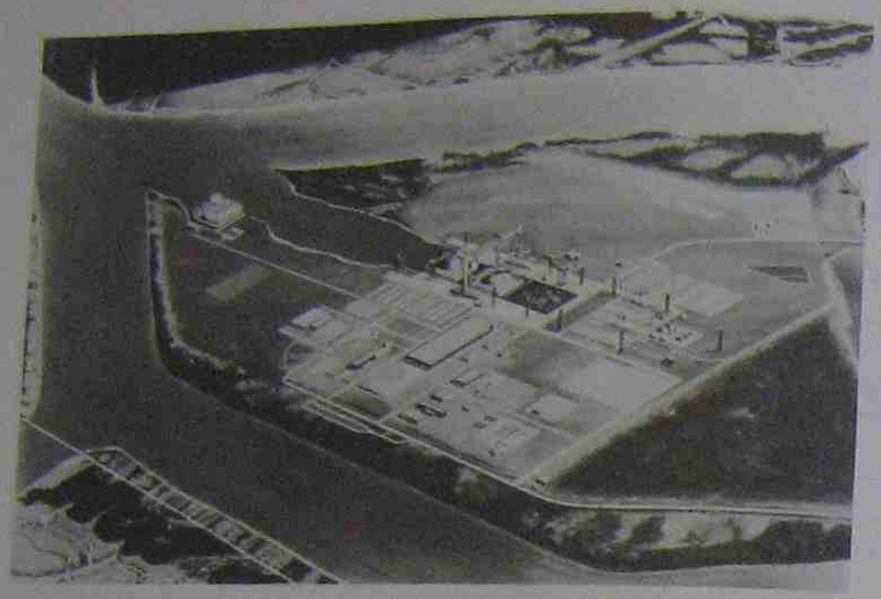


Courtesy Offshore Power Systems

Fig. 3-14. Close-up illustration of a floating nuclear plant.

This oil shale was formed by a process similar to that which created crude petroleum. However, there was never enough underground heat or pressure to convert the organic sediment to the same consistency as oil. Instead, a waxy hydrocarbon called *kerogen* was produced. This compound is mixed with fine rock and is referred to as oil shale.

Extracting crude petroleum from this substance is a very complex process which starts with either underground or strip mining. The mined rock is crushed and then heated to produce a raw oil which, in turn, must be upgraded to a usable level. All of these operations could take place at the mining site. In addition, large



Courtesy Offshore Power Systems

Fig. 3-15. Manufacturing facility for floating nuclear plants.

amounts of shale waste must be removed. The resulting waste substance is about the consistency and color of fireplace soot. The waste occupies more volume than the original oil-shale formations. The potential impact of oil-shale development is questionable. Vast quantities of land might be disturbed. There are definitely many factors to consider in addition to our energy needs.

FLOATING NUCLEAR POWER PLANTS

A unique concept in electrical power production is called a floating nuclear power plant. Floating nuclear plants are nuclear-fission plants which are mounted on huge floating platforms for operation on the water. The proposed layout of a floating nuclear power plant is shown in Fig. 3-13. These systems are presently planned for use on the Atlantic Ocean. Notice the breakwaters which surround the power plant to protect it from waves and ship collisions.

A close-up illustration of a floating nuclear plant is shown in Fig. 3-14. This unit could be located on rivers, inlets, or in the ocean. The plant is manufactured on land and then transported to the area where it will be used. The electrical power produced by the plant can be distributed by underwater cables to the shore. The power lines could then be connected to onshore overhead power-transmission lines. The floating nuclear power plants can be mass-produced, unlike conventional nuclear plants which are individually built. The first unit is planned to go into operation by 1984. They are built at a manufacturing facility such as the one shown in Fig. 3-15.

Floating nuclear plants have several advantages over other power systems. There are obvious ecological benefits. A plant located on the ocean would have less thermal effect on the water due to heat dissipation over a large body of water. Also, these units would not require the use of land for locating power plants. They are flexible since they can be located on rivers, inlets, or oceans. However, they are primarily for use on the ocean.

CHAPTER 4

Alternating-Current Power Systems

Some of the basics of alternating-current power systems were discussed in Chapter 1. You should already have an understanding of the effects of resistance, inductance, and capacitance in ac circuits. Therefore, this chapter will deal primarily with the systems which are used to produce ac electrical power.

The vast majority of the electrical power produced in the United States is alternating current. Massive mechanical generators at power plants throughout our country provide the necessary electrical power to supply our homes and industries. Most generators produce three-phase alternating current; however, single-phase generators are also used for certain applications of a smaller nature. The operation of mechanical generators relies upon a fundamental principle of electricity called electromagnetic induction.

ELECTROMAGNETIC INDUCTION

The basic principle which allows electrical power to be produced by alternators was discovered in the early 1800s. The principle of electromagnetic induction was one of the most important discoveries in the development of modern technology. Without electrical power, our lives would certainly be different. Electromagnetic induction, as the name implies, involves electricity and magnetism. When electrical conductors, such as alternator windings, are moved within a magnetic field, an electrical current is developed in the conductors. The electrical current produced in this way is called an induced current. A simplified illustration showing how induced electrical current is developed is shown in Fig. 4-1.

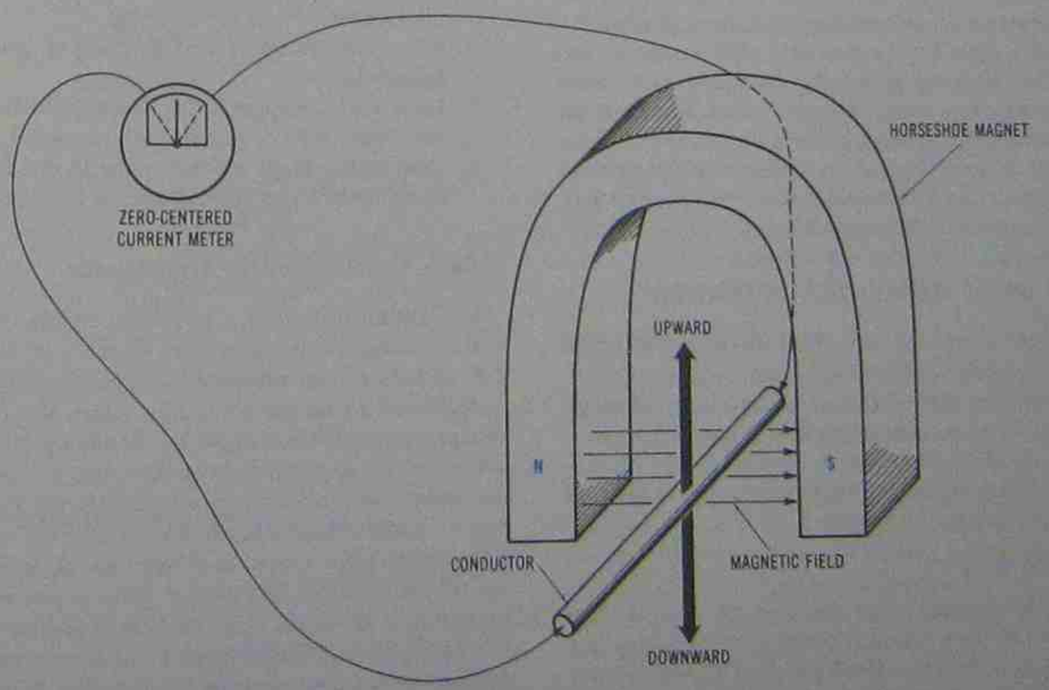


Fig. 4-1. Electromagnetic induction.

A conductor is placed within the magnetic field of a horseshoe magnet so that the left side of the magnet has a north polarity (N) and the right side has a south polarity (S). Magnetic lines of force travel from the north polarity of the magnet to the south polarity. The ends of the conductor are connected to a current meter to measure the induced current. The meter is the zero-centered type so that its needle can move either to the left or to the right. When the conductor is moved, current will flow through the conductor. Electromagnetic induction takes place whenever there is relative motion between the conductor and the magnetic field. Either the conductor can be moved through the magnetic field or the conductor can be held stationary and the magnetic field can be moved past it. Thus, current will be induced as long as there is a relative motion between the conductor and magnetic field.

If the conductor shown in Fig. 4-1 is moved upward, the needle of the meter will move to the right. However, if the conductor is moved downward, the needle of the meter will deflect to the left. This shows that the direction of movement of the conductor within the magnetic field determines the direction of current flow. In one case, the current flows through the conductor from the front of the illustration to the back. In the other situation, the current travels from the back to the front. The direction of current flow is indicated by the direction of the meter deflection. The principle demonstrated here is the basis for electrical power generation.

In order for an induced current to be developed, the conductor must have a complete path or closed circuit. The meter in Fig. 4-1 was connected to the conductor to make a complete current path. If there is no closed circuit, electromagnetic induction cannot take place. It is important to remember that an induced current causes an induced electromotive force (voltage) across the ends of the conductor.

BASIC GENERATOR OPERATION

As stated previously, the operation of electrical generators used today depends upon the principle of electromagnetic induction. When conductors move through a magnetic field or a magnetic field is moved past conductors, an induced current is developed. The current that is induced into the conductors produces an induced electromotive force or voltage.

Left-Hand Rule

We can determine the direction of current flow through a moving conductor within a magnetic field by using the *left-hand rule*. Refer to Fig. 4-2 and use your left hand in the following manner:

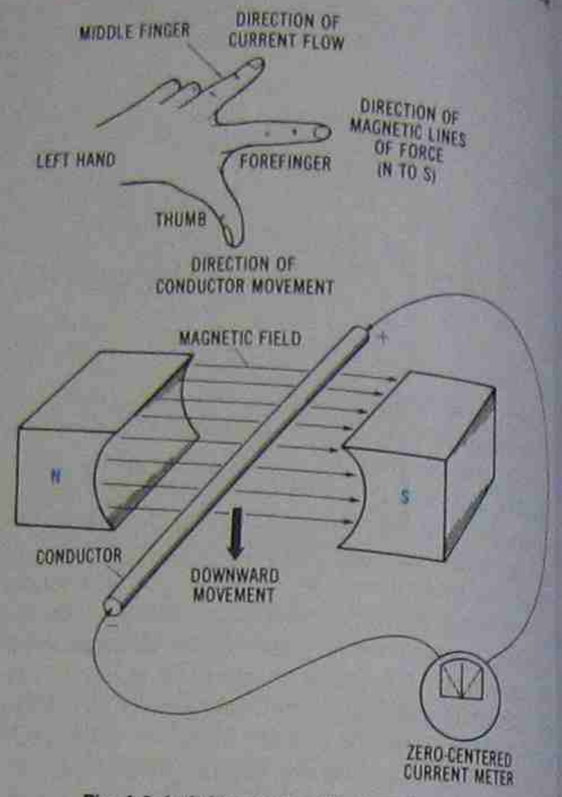


Fig. 4-2. Left-hand rule of induced current.

1. Arrange your thumb, forefinger, and middle finger so that they are at approximately right angles to one another.
2. Point your thumb in the direction of conductor movement.
3. Point your forefinger in the direction of the magnetic lines of force (from north to south).
4. Your middle finger will now point in the direction of induced current flow (negative to positive).

Voltage Development in a Generator

It is known that when a conductor moves across a certain number of magnetic lines of force in one second, an induced electromotive force (emf) of one volt is developed across the conductor. Thus, the induced voltage value can be changed by modifying either the strength of the magnetic field or the speed of conductor movement through the magnetic field. If the magnetic field is made stronger, more voltage will be induced. If the conductor is moved at a faster speed, more voltage will be induced. Likewise, if more conductors are concentrated within the magnetic field, a greater voltage will be developed. These rules of electromagnetic induction are very important for the operation of mechanical generators which produce electrical power.

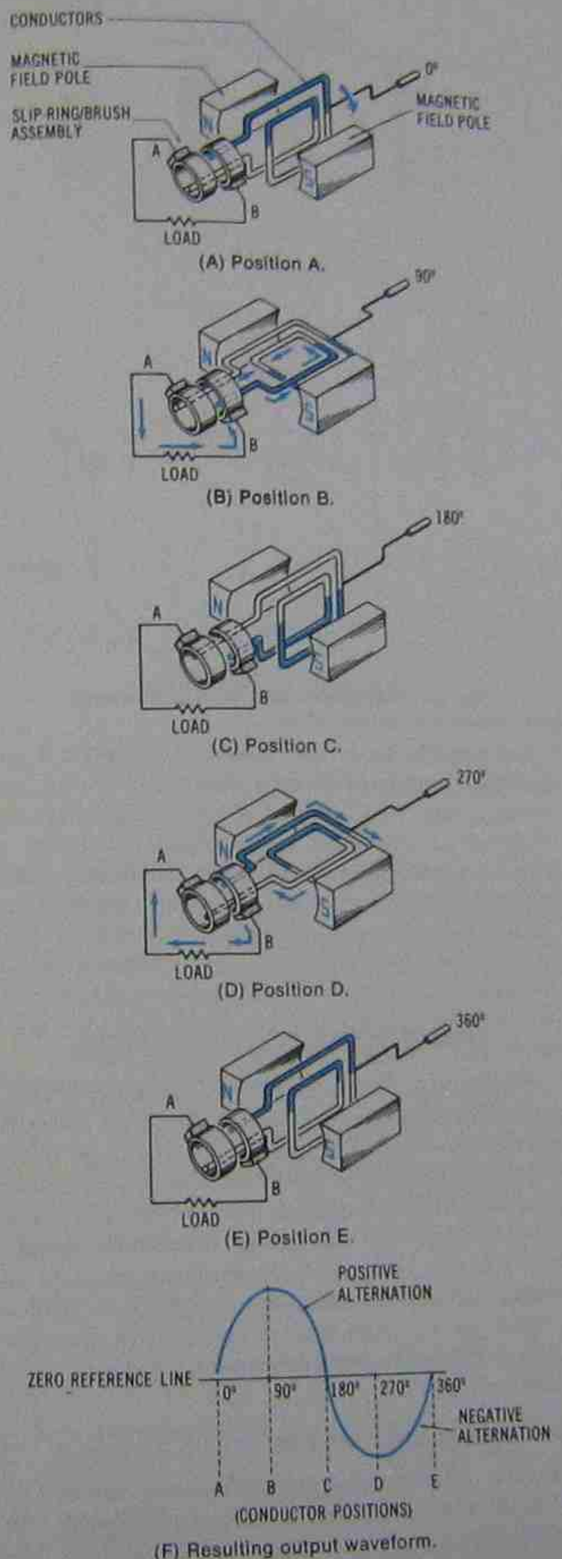


Fig. 4-3. Basic principle of a single-phase alternator.

SINGLE-PHASE AC POWER SYSTEMS

Electrical power can be produced by single-phase generators, commonly called alternators. The principle of operation of a single-phase alternator is shown in Fig. 4-3. In order for a generator to convert mechanical energy into electrical energy, three conditions must exist:

1. There must be a magnetic field developed.
2. There must be a group of conductors adjacent to the magnetic field.
3. There must be relative motion between the magnetic field and the conductors.

These conditions are necessary in order for electromagnetic induction to take place.

Generator Construction

Generators used to produce electrical power require some form of mechanical energy. This mechanical energy is used to move electrical conductors through the magnetic field of the generator. Fig. 4-3 shows the basic parts of a mechanical generator. A generator has a stationary part and a rotating part. The stationary part is called the *stator* and the rotating part is called the *rotor*. The generator has magnetic *field poles* of north and south polarities. Also, the generator must have a method of producing a rotary motion or a *prime mover* connected to the generator shaft. There must also be a method of electrically connecting the rotating conductors to an external circuit. This is done by a *slip ring/brush assembly*. The stationary brushes are made of carbon and graphite. The slip rings used on ac generators are made of copper. They are permanently mounted on the shaft of the generator. The two slip rings connect to the ends of a *conductor loop*. When a *load* is connected, a closed external circuit is made. With all of these generator parts functioning together, electromagnetic induction can take place and electrical power can be produced.

Generating AC Voltage

Fig. 4-3 shows a magnetic field developed by a set of permanent magnets. Conductors that can be rotated are placed within the magnetic field and they are connected to a load device by means of a slip ring/brush assembly. Fig. 4-3 simulates a single-phase alternator.

In position A (Fig. 4-3A), the conductors are positioned so that the minimum amount of magnetic lines of force are "cut" by the conductors as they rotate. No current is induced into the conductors at position A and the resulting current flow through the load will be zero. If the conductors are rotated 90° in a clockwise direction to position B (Fig. 4-3B), they will pass

from the minimum lines of force to the most concentrated area of the magnetic field. At position B, the induced current will be maximum, as shown by the waveform diagram of Fig. 4-3F. Note that the induced current rises gradually from the zero reference line to a maximum value at position B. As the conductors are rotated another 90° to position C (Fig. 4-3C), the induced current becomes zero again. No current flows through the load at this position. Note, in the diagram of Fig. 4-3F, how the induced current drops gradually from maximum to zero. This part of the induced ac current (from 0° to 180°) is called the positive alternation. Each value of the induced current, as the conductors rotate from the 0° position to the 180° position, is in a positive direction. This action could be observed visually if a meter was connected in place of the load.

When the conductors are rotated another 90° to position D (Fig. 4-3D), they once again pass through the most concentrated portion of the magnetic field. Maximum current is induced into the conductors at this position. However, the direction of the induced current is in the opposite direction as compared with position B. At the 270° position, the induced current is maximum in a negative direction. As the conductors are rotated to position E (same as at position A), the induced current is minimum once again. Note in the diagram of Fig. 4-3E how the induced current decreases from its maximum negative value back to zero again (at the 360° position). The part of the induced current from 180° to 360° is called the negative alternation. The complete output, which shows the induced current through the load, is called an alternating-current waveform. As the conductors continue to rotate through the magnetic field, the cycle is repeated.

Alternating-Current Sine Wave

The induced current produced by the method discussed above is in the form of a sinusoidal waveform or sine wave. This waveform is referred to as a sine wave due to its mathematical origin, based on the trigonometric sine function. The current induced into the conductors, shown in Fig. 4-3, varies as the sine of the angle of rotation between the conductors and the magnetic field. This induced current produces a voltage. The instantaneous voltage induced into a single conductor can be expressed as:

$$V_i = V_{max} \times \sin \theta$$

where,

V_i is the instantaneous induced voltage,
V_{max} is the maximum induced voltage,
θ is the angle of conductor rotation from the zero reference.

TRIGONOMETRIC SINE VALUES

Degrees	Sine	Degrees	Sine
0/360	0.000	180	0.000
30	0.500	210	0.500
60	0.866	240	0.866
90	1.000	270	1.000
120	0.866	300	0.866
150	0.500	330	0.500

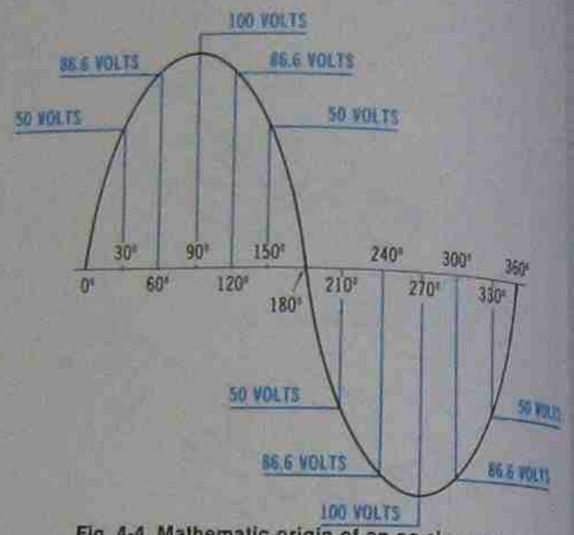


Fig. 4-4. Mathematic origin of an ac sine wave.

For example, at the 30° position (Fig. 4-4), if the maximum voltage is 100 volts, then

$$V_i = 100 \times \sin \theta.$$

Refer to Appendix A to find that the sine of 30° = 0.5, then

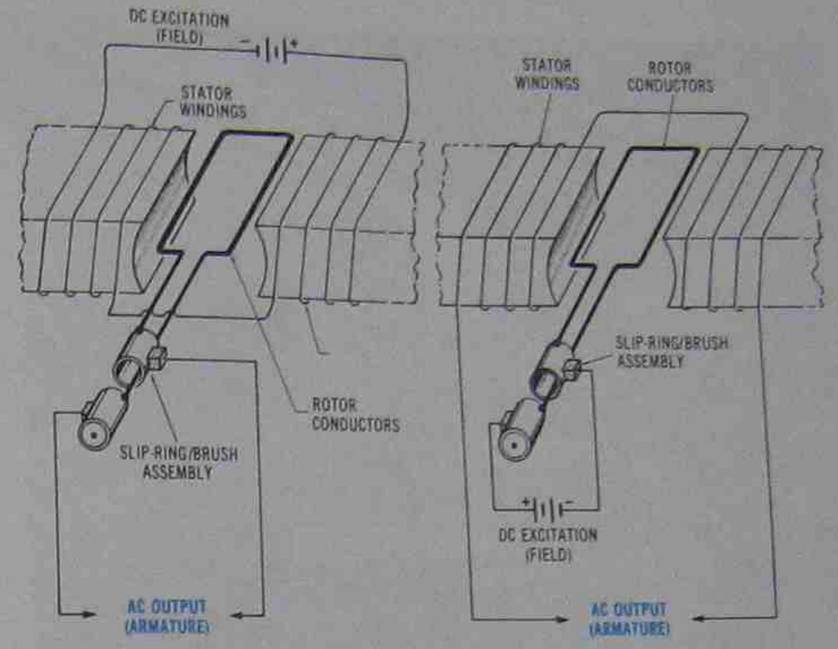
$$V_i = 100 \times 0.5$$
$$= 50 \text{ volts.}$$

SINGLE-PHASE AC GENERATORS

Although much single-phase electrical power is used, particularly in the home, very little electrical power is produced by single-phase alternators. The single-phase electrical power used in the home is usually developed by three-phase alternators and then converted to single-phase electricity by the power distribution system. There are two basic methods which can be used to produce single-phase alternating current. One method is called the rotating-armature method and the other is the rotating-field method. These methods are illustrated in Fig. 4-5.

Rotating Armature Method

In the rotating-armature method, shown in Fig. 4-4A, an alternating-current voltage is induced into the conductors of the rotating part of the machine. The electromagnetic field is developed by a set of stationary



(A) Rotating-armature method. (B) Rotating-field method.

Fig. 4-5. The two basic methods of generating single-phase alternating current.

pole pieces. Relative motion between the conductors and the magnetic field is provided by a prime mover or mechanical-energy source connected to the shaft (which is a part of the rotor assembly). Prime movers may be steam turbines, gas turbines, hydraulic turbines, gasoline engines, diesel engines, or possibly gas engines or electric motors. Remember that all generators convert mechanical energy into electrical energy, as shown in Fig. 4-6. Only small power ratings can be used with the rotating-armature type of alternator. The major disadvantage of this method is that the ac voltage is extracted from a slip ring/brush assembly (see Fig. 4-5A). A high voltage could produce tremendous sparking or arc-over between the brushes and the slip rings. The maintenance involved in replacing brushes and repairing the slip-ring commutator assembly would be very time consuming and expensive. Therefore, this method is used only for alternators with low power ratings.

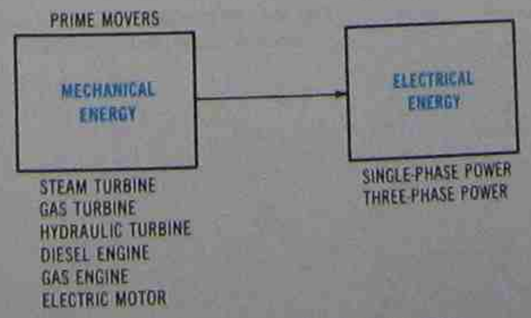


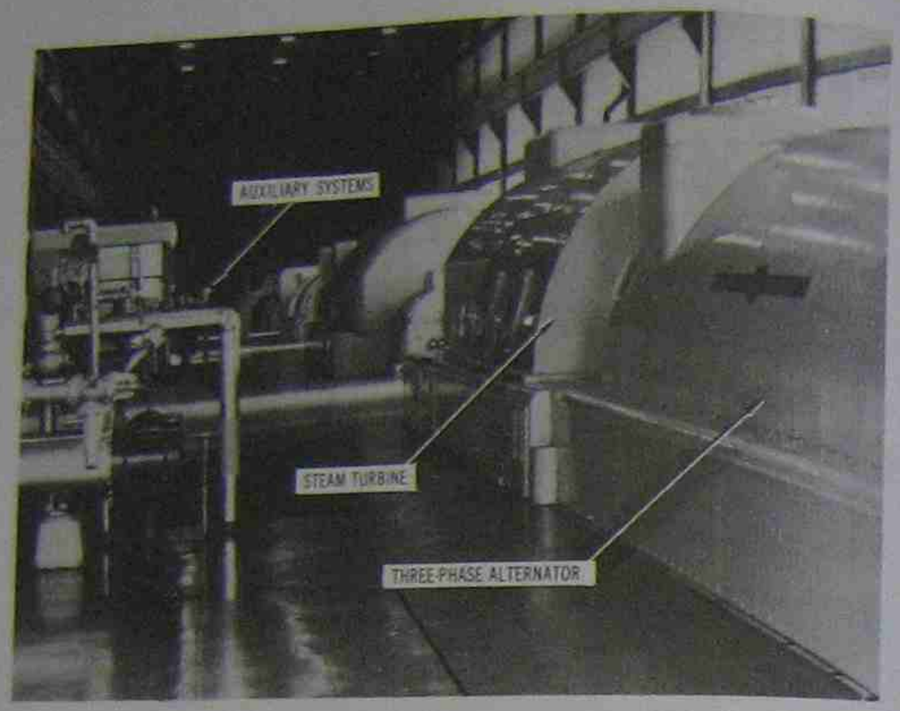
Fig. 4-6. Energy conversion by generators.

Rotating-Field Method

The rotating-field method, shown in Fig. 4-5B, is used for alternators capable of producing larger amounts of power. The dc-excitation voltage which develops the magnetic field is applied to the rotating portion of the machine. The ac voltage is induced into the stationary conductors of the machine. Since the dc-excitation voltage is a much lower value than the ac voltage that is produced, maintenance problems associated with the slip ring/brush assembly are minimized. In addition, the conductors of the stationary portion of the machine may be larger so as to handle more current since they do not rotate.

THREE-PHASE AC GENERATORS

The vast majority of electrical power produced in the United States is three-phase power. A large, commercial generator is shown in Fig. 4-7. Most generators which produce three-phase voltage look similar to this one. Due to their large power ratings, three-phase generators utilize the rotating field method. A typical three-phase generator in a power plant might have 250-volts dc excitation applied to the rotating field through the



Courtesy General Electric Co.

Fig. 4-7. A large, commercial, three-phase ac generator.

slip ring/brush assembly while 13.8 kilovolts ac is induced into the stationary conductors.

Commercial power systems use many three-phase alternators connected in parallel to supply their regional load requirements. Normally, industrial loads represent the largest portion of the load on our power systems. The residential (home) load is somewhat less. Due to the vast load that has to be met by the power systems, three-phase generators have high power ratings. Name plate data for a typical commercial three-phase alternator is shown in Fig. 4-8. Note the large values for each of the nameplate ratings.

Generation of Three-Phase Voltage

The basic construction of a three-phase ac generator is shown in Fig. 4-9, with its resulting output waveform

GENERAL ELECTRIC
TURBINE-GENERATOR

STEAM TURBINE

NO. 126917

RATING	66000 KW	3600 RPM	21 STAGES
STEAM PRESSURE	1750 PSIG TEMP. 950 F	EXHAUST PRESSURE 1.5" HG. ABS.	

GENERATOR

NO. 9287069 HYDROGEN COOLED

TYPE ATB 2 POLES 60 CYCLES

3 PH. Y CONNECTED FOR 13800 VOLTS

EXCITATION 250 VOLTS

TEMP RISE GUARANTEED NOT TO EXCEED

45 C ON ARMATURE BY DETECTOR

74 C ON FIELD BY RESISTANCE

	RATING	CAPABILITY 15 PSIG	CAPABILITY 0.5 PSIG
GAS PRESSURE	30 PSIG		
KVA	88235	81176	70588
KILOWATTS	75000	69000	60000
ARMATURE AMP	3691	3396	2953
FIELD AMP	721	683	576
POWER FACTOR	0.85	0.85	0.85

CAUTION! BEFORE INSTALLING, OPERATING OR DISMANTLING READ INST. GEI-64582

SCHENECTADY, N.Y. MADE IN U.S.A.

Courtesy General Electric Co.

Fig. 4-8. Nameplate data for a commercial three-phase alternator.

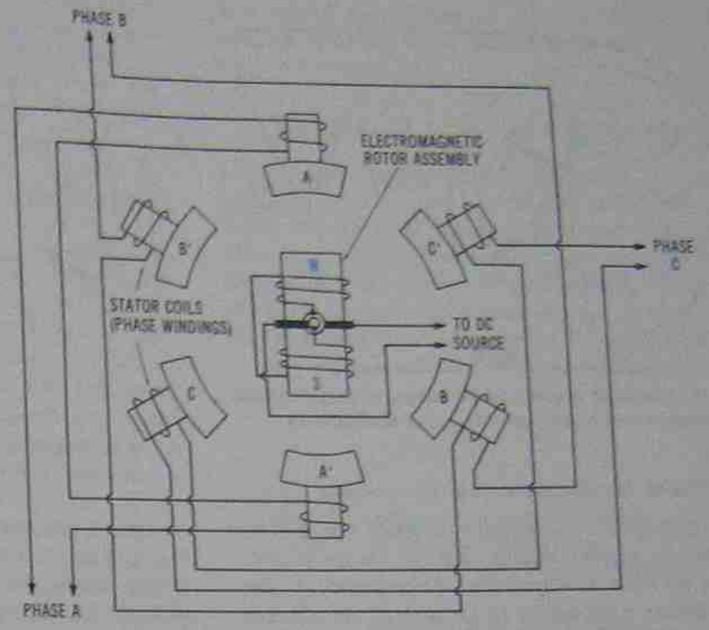


Fig. 4-9. Simplified drawing showing the basic construction of a three-phase ac generator.

given in Fig. 4-10. Note that three-phase generators must have at least six stationary poles or two poles for each phase. The three-phase generator shown in the drawing is a rotating-field type generator. The magnetic field is developed electromagnetically by a direct-current voltage. The dc voltage is applied from an external power source through a slip ring/brush assembly to the windings of the rotor. The magnetic polarities of the rotor as shown are north at the top and south at the bottom of the illustration. The magnetic lines of force would be developed around the outside of the electromagnetic rotor assembly.

Through electromagnetic induction, a current can be induced into each of the stationary (stator) coils of the generator. Since the beginning of phase A is physically located 120° from the beginning of phase B, the induced currents will be 120° apart. Likewise, the beginning of phase B and phase C are located 120° apart. Thus, the voltages developed due to electromagnetic induction are 120° apart, as shown in Fig. 4-10. Voltages are developed in each stator winding as the electromagnetic field rotates within the enclosure which houses the stator coils.

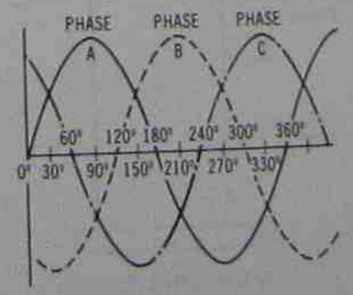


Fig. 4-10. Output waveform of a three-phase ac generator.

Three-Phase Connection Methods

In Fig. 4-9, poles A′, B′, and C′ represent the beginnings of each of the phase windings of the alternator. Poles A, B, and C represent the ends of each of the phase windings. There are two methods which may be used to connect these windings together. These methods are called wye and delta connections.

Three-Phase Wye-Connected Generators

The windings of a three-phase generator can be connected in a wye configuration by connecting the beginnings or the ends of the windings together. The other ends of the windings become the three-phase power lines from the generator. A three-phase wye-connected generator is illustrated in Fig. 4-11. Notice that the beginnings of the windings (poles A′, B′, and C′) are connected together. The other ends of the windings (poles A, B, and C) are the three-phase power lines that are connected to the load to which the generator will supply power.

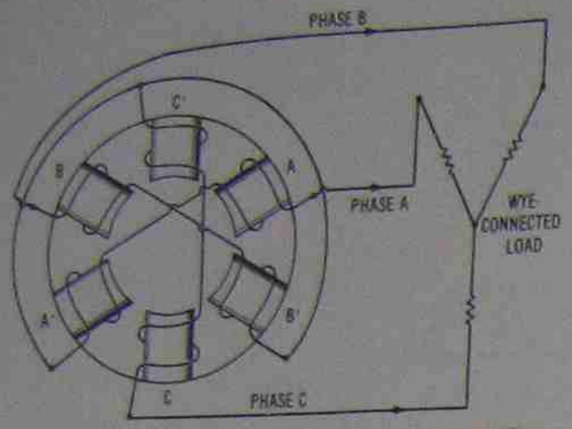


Fig. 4-11. Simplified drawing of the stator of a three-phase generator that is connected in a wye configuration.

Three-Phase Delta-Connected Generators

The windings of a three-phase generator may also be connected in a delta arrangement, as shown in Fig. 4-12. In the delta configuration, the beginning of one phase winding is connected to the end of the adjacent phase winding. Thus, the beginnings and ends of all adjacent phase windings are connected together. The voltage, current, and power characteristics of three-phase wye and delta connections were discussed earlier in Chapter 1.

Advantages of Three-Phase Power

Three-phase power is used primarily for industrial and commercial applications. Many types of industrial equipment use three-phase alternating-current power because the power produced by a three-phase voltage

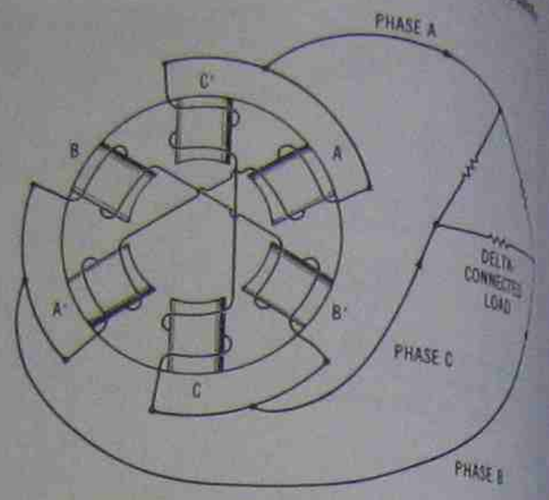
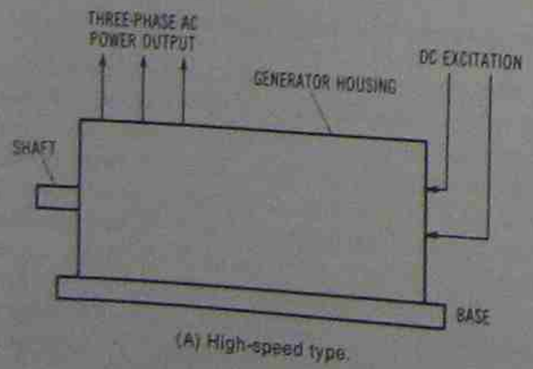


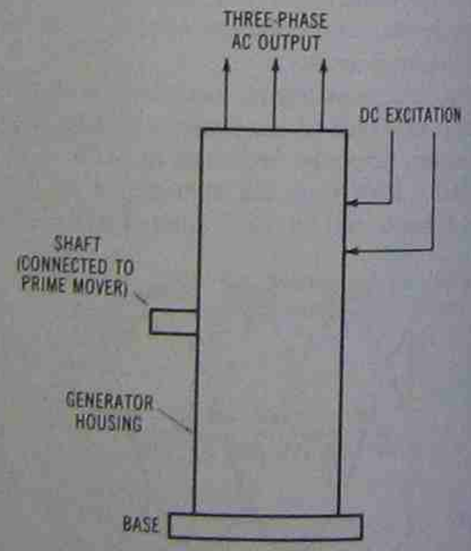
Fig. 4-12. Simplified drawing of the stator of a three-phase generator that is connected in a delta configuration.

source, as compared to single-phase power, is less pulsating. You can see this effect by observing that a peak voltage occurs every 120° in the three-phase waveform of Fig. 4-10. A single-phase voltage has a peak voltage only once every 360° (Fig. 4-3). This comparison is somewhat similar to comparing the power developed by an eight-cylinder engine to the power developed by a four-cylinder engine. The eight-cylinder engine provides smoother, less-pulsating power. The effect of smoother power development on electric motors (with three-phase voltage applied) is that it produces a more uniform torque in the motor. This factor is very important for the large motors that are used in industry.

Three separate single-phase voltages can be derived from a three-phase transmission line and it is more



(A) High-speed type.



(B) Low-speed type.

Fig. 4-13. High- and low-speed ac generators.

economical to distribute three-phase power from plants to consumers that are located a considerable distance away. Fewer conductors are required to distribute the three-phase voltage. Also, the equipment which uses three-phase power is physically smaller in size than similar single-phase equipment.

HIGH-SPEED AND LOW-SPEED GENERATORS

Generators can also be classified as either high-speed or low-speed types (Fig. 4-13). The type of generator used depends upon the prime mover used to rotate the generator. High-speed generators are usually driven by steam turbines. The generator is smaller in diameter and longer than a low-speed generator. The high-speed generator ordinarily has two stator poles per phase; thus, it will rotate at 3600 rpm to produce a 60-hertz frequency.

Low-speed generators are larger in diameter and not as long as high-speed machines. Typical low-speed generators are used at hydroelectric power plants. They have large-diameter revolving fields that use many poles. The number of stator poles used could, for example, be twelve for a 600-rpm machine or eight for a 900-rpm generator. Notice that a much larger number of poles is required for low-speed generators.

GENERATOR FREQUENCIES

The frequency of the sinusoidal waveforms (sine waves) produced by an alternating-current generator is usually 60 hertz. One cycle of alternating current is generated when a conductor makes one complete revolution past a set of north and south field poles. A speed of 60 revolutions per second (3600 revolutions per minute) must be maintained to produce 60 hertz. The frequency of an alternating-current generator (alternator) may be expressed as:

$$f = \frac{\text{number of poles per phase} \times \text{speed of rotation (rpm)}}{120}$$

where,

f is the frequency in hertz.

Note that if the number of poles is increased, the speed of rotation may be reduced while still maintaining a 60-Hz frequency.

GENERATOR VOLTAGE REGULATION

As an increased electrical load is added to an alternator, it tends to slow down. The decreased speed causes the generated voltage to decrease. The amount of voltage change depends on the generator design and the type of load connected to its terminals. The amount of change in generated voltage from a no-load condition to a rated full-load operating condition is referred to as *voltage regulation*. Voltage regulation may be expressed as:

$$VR = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100$$

where,

VR is the voltage regulation in percent,
V_{NL} is the no-load terminal voltage,
V_{FL} is the rated full-load terminal voltage.

GENERATOR EFFICIENCY

Generator efficiency is the ratio of the power output in watts to the power input in horsepower. The efficiency of a generator may be expressed as:

$$\text{Efficiency } (\%) = \frac{P_{out}}{P_{in}} \times 100$$

where,

P_{in} is the power input in horsepower,
P_{out} is the power output in watts.

To convert horsepower to watts, remember that 1 horsepower = 746 watts. The efficiency of a generator usually ranges from 70% to 85%.

PROBLEMS

1. If the peak voltage of a single-phase ac generator is 320 volts, what are the instantaneous induced voltages after an armature conductor has rotated the following number of degrees:

   a. 25°
   b. 105°
   c. 195°
   d. 290°
   e. 335°

2. A three-phase ac (wye-connected) generator has a phase voltage of 120 volts and phase currents of 10 amperes. What is its

   a. Line voltage
   b. Line current
   c. Power per phase
   d. Total power at 1.0 power factor
   e. Total power at 0.7 power factor

3. A three-phase ac (delta-connected) generator has a line voltage of 480 volts, line currents of 7.5 amperes, and operates at a power factor of 0.85. Calculate:

   a. Phase voltage
   b. Phase current
   c. Power per phase
   d. Total power

4. Calculate the operating frequencies of the following generators:

   a. Single-phase, 2-pole, 3600 rpm
   b. Single-phase, 4-pole, 1800 rpm
   c. Three-phase, 12-pole, 1800 rpm
   d. Three-phase, 6-pole, 3400 rpm

5. Calculate the voltage regulation of ac generators with the following no-load and full-load voltage values:

   a. $V_{NL} = 120$ volts, $V_{FL} = 115$ volts
   b. $V_{NL} = 220$ volts, $V_{FL} = 210$ volts
   c. $V_{NL} = 480$ volts, $V_{FL} = 478$ volts

6. Calculate the efficiency of the following ac generators:

   a. Power input = 20 hp, power output = 12 kW
   b. Power input = 2.5 hp, power output = 1200 watts
   c. Power input = 4.25 hp, power output = 3 kW

CHAPTER 5

Direct-Current Power Systems

Alternating current is used in greater quantities than direct current; however, many important operations are dependent upon direct-current power. Industries use direct-current power for many specialized processes. Electroplating and dc variable-speed motor drives are only two examples which show the need for direct-current power to sustain industrial operations. We use direct-current power to cause our automobiles to start and many types of portable equipment in the home use direct-current power. Most of the electrical power produced in the United States is three-phase alternating current and this three-phase ac power may be easily converted to direct current for industrial or commercial use. Direct current is also available in the form of primary and secondary chemical cells. These cells are used extensively. In addition, direct-current generators are also used to supply power for specialized applications.

DIRECT-CURRENT PRODUCTION USING CHEMICAL CELLS

The conversion of chemical energy into electrical power can be accomplished by the use of electrochemical cells. A cell is composed of two dissimilar metals which are immersed in a conductive liquid or paste called an electrolyte. Chemical cells are classified as either primary cells or secondary cells. Primary cells are ordinarily not usable after a certain period of time. After this period of time, its chemicals can no longer produce electrical energy. Secondary cells can be renewed after they are used by reactivating the chemical process that is used to produce electrical energy. This reactivation is known as charging. Both primary cells and secondary cells have many applications. When two or more cells are connected in series, they form a battery.

CHARACTERISTICS OF PRIMARY CELLS

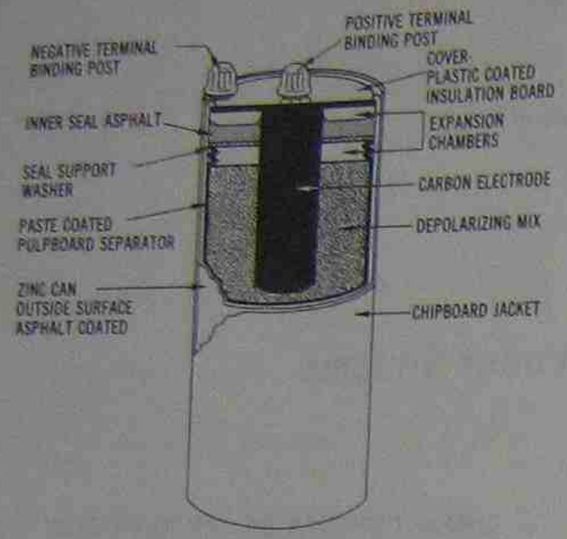
The operational principle of a primary cell involves the placing of two unlike conductive materials called electrodes into a conductive solution called an electrolyte. When the chemicals which compose the cell are brought together, their molecular structures are altered. During this alteration, their atoms may either retain additional electrons or leave behind some of their electrons. These atoms then have either a positive or a negative electrical charge and are referred to as ions. The ionization process thus develops a chemical solution capable of conducting an electrical current. Two types of carbon-zinc primary cells are shown in Fig. 5-1.

When an external load device, such as a lamp, is connected to a cell, a current will flow from one electrode to the other through the electrolyte material. Current leaves the cell through its negative electrode, flows through the load device, then reenters the cell through its positive electrode, as shown in Fig. 5-2. Thus, a complete circuit is established between the cell (source) and the lamp (load).

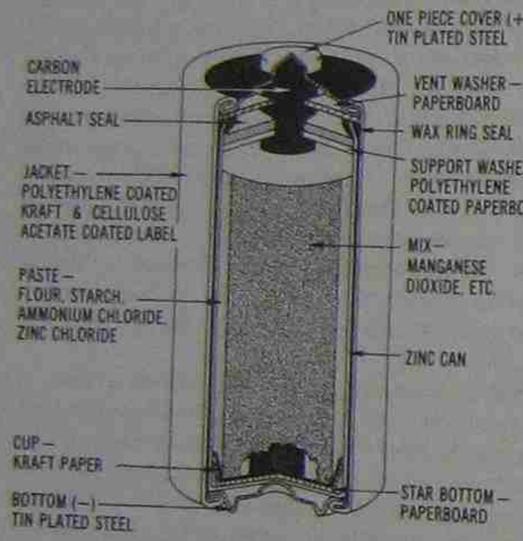
The voltage developed by a primary cell is dependent upon the electrode materials and the type of electrolyte used. The familiar carbon-zinc cells of Fig. 5-1 produce approximately 1.5 volts. The negative electrode of the cell is the zinc container and the positive electrode is a carbon rod. A sal ammoniac paste which acts as the electrolyte is placed between the electrodes. This type of cell is usually called a dry cell.

Internal Resistance of Cells

An important characteristic of a chemical cell is its internal resistance. Since a cell conducts electrical current, its resistance depends on its cross-sectional area, the length of its current path, the type of materials used,



(A) No. 6 dry cell.



(B) Standard round cell.

Courtesy Union Carbide Corp.

Fig. 5-1. Cutaway drawings of two types of carbon-zinc primary cells.

and the operational temperature. The amount of current which a cell will deliver to a load is expressed as:

$$I = \frac{V}{R_i + R_L}$$

where,

I is the current in amperes,
V is the voltage or electromotive force (emf) of the cell in volts,
R_i is the internal resistance of the cell in ohms,
R_L is the resistance of the load in ohms.

This formula and the circuit that illustrates it are shown in Fig. 5-3. The formula shows that when a cell

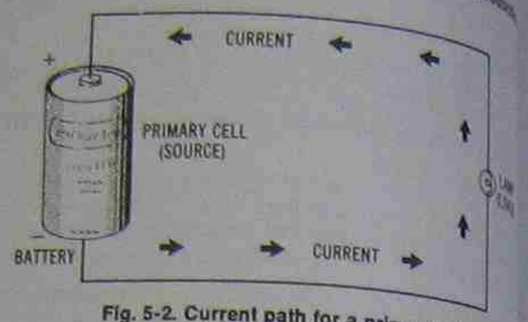


Fig. 5-2. Current path for a primary cell.

delivers current to a load, some of the voltage develop must be used to overcome the internal resistance the cell. As load current increases, the voltage dr (I × R) within the cell increases. This increased volta drop causes the output voltage (V_o) of the cell to de crease. Thus,

$$V_o = V - IR_i$$

where,

V_o is the output voltage of the cell in volts,
V is the no-load cell voltage in volts,
I is the load current in amperes,
R_i is the internal resistance of the cell in ohms.

Modifying this formula to solve directly for R_i w obtain:

$$R_i = \frac{V - V_o}{I}.$$

The same method is used to determine the internal re sistance of all voltage sources, including primary cel secondary cells, and generators.

Applications of Primary Cells

There are many types of primary cells available to day, with unlimited applications. The carbon-zinc o Lechanche cell discussed previously is the most often used type of dry cell. This cell has a low initial cos and is available in a variety of sizes. It is used prima

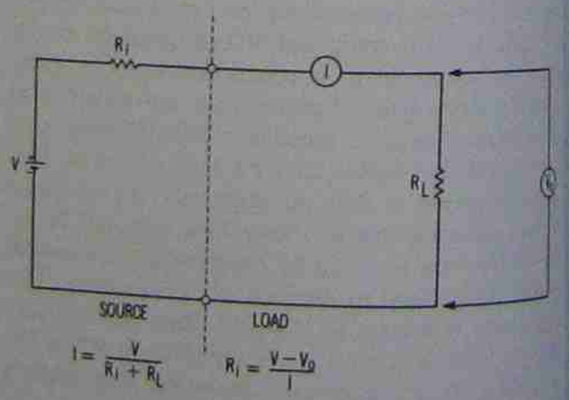


Fig. 5-3. Illustrating the internal resistance of a cell.

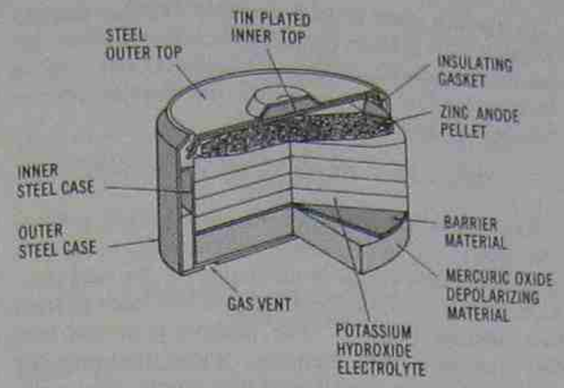


Fig. 5-4. Cutaway drawing of a mercury primary cell.

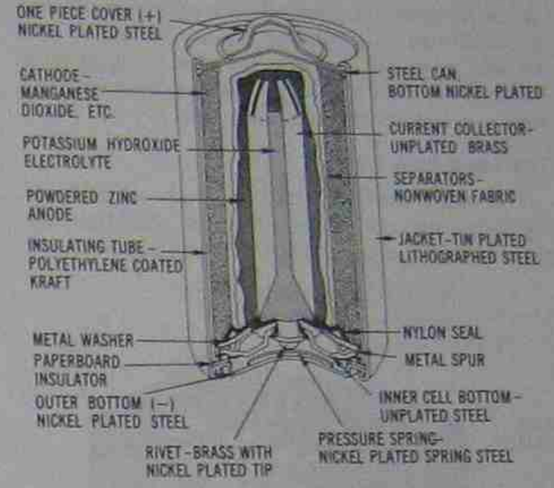
ily for portable equipment or instruments. For uses which require a higher voltage or current than one cell can deliver, manufacturers combine several cells in series, parallel, or series-parallel arrangements to form batteries suitable for specialized applications. Carbon-zinc batteries can be obtained in voltage ratings from 1.5 volts, at over 1-ampere capability, up to about 3000 volts.

Mercury Cells—Another type of primary cell is the mercury or zinc-mercuric oxide cell shown in Fig. 5-4. This cell was developed as an improvement of the carbon-zinc cell. This type of cell has a more constant voltage output, a longer active service time, and a smaller physical size. However, the mercury cell is more expensive and produces a voltage of 1.35 volts, which is lower than the carbon-zinc cell.

Alkaline Cells—An alkaline or zinc-magnesium dioxide cell, shown in Fig. 5-5, is another type of primary cell. These cells have very low internal resistance and a voltage per cell of 1.5 volts. Due to their low internal resistance, alkaline cells will supply higher currents to the electrical loads connected to them. Alkaline cells are capable of a much longer service life than the equivalent carbon-zinc cells.

Nuclear Cells—A recent source of direct-current power that has been developed is the nuclear cell. Such cells convert the energy given off by atomic nuclei into electrical energy. At present, a high-voltage type (thousands of volts with a picoampere current capacity) and a low-voltage type (approximately 1 volt with a microampere current capability) are available.

The illustration of Fig. 5-6 shows the design of one type of nuclear cell. The radioactive source is connected to one electrode of the cell. The source used here is tritium gas absorbed in zirconium metal, which emits beta particles. The carbon-collector electrode collects these beta particles as they are emitted from the tritium source, thus producing an electrical charge. The elec-



Courtesy Union Carbide Corp.

Fig. 5-5. Cutaway drawing of an alkaline primary cell.

trodes are separated by either a vacuum or some other type of dielectric, which electrically isolates the two electrodes. The nuclear cell shown in Fig. 5-6 has air removed through the center tube to form the vacuum inside which isolates the positive and negative electrodes. The direct-current output produced by this cell is extracted through terminals connected to the tritium source (negative) and to the carbon collector (positive). The output of this cell is dependent upon the nuclear energy generated by the tritium source; therefore, the voltage output decreases as the cell ages.

CHARACTERISTICS OF SECONDARY CELLS

Regardless of the type of primary cell used, its usable time is limited. When its chemicals are expended, it becomes useless. This disadvantage is overcome by

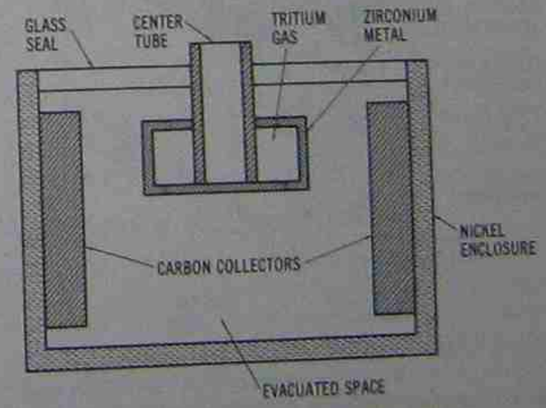
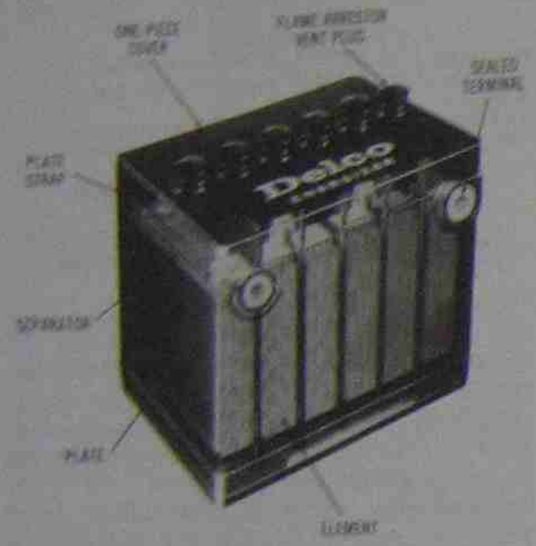


Fig. 5-6. Cutaway drawing of a nuclear cell.

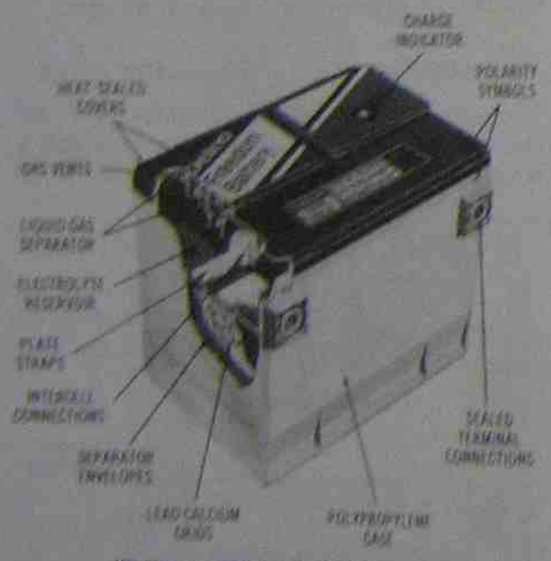
secondary cells. The chemicals of a secondary cell may be reactivated by a charging process. Secondary cells are also called storage cells. The most common types of secondary cells are the lead-acid, nickel-iron (Edison) cell, and the nickel-cadmium cells.

The Lead-Acid Cell

The widely used lead-acid cell, such as shown in Fig. 5-7, is one type of secondary cell. The electrodes of the lead-acid cell are made of lead and lead peroxide.



(A) Standard lead-acid battery.



(B) New sealed-type lead-acid battery.

Courtesy AC-Delco Div., General Motors Corp.

Fig. 5-7. Cutaway drawing of two types of batteries composed of lead-acid secondary cells.

The positive plate is lead peroxide (PbO_2) and the negative plate is lead (Pb). The electrolyte is dilute sulphuric acid (H_2SO_4). When the lead-acid cell supplies current to a load connected to it, the chemical process can be expressed as:

$$PbO_2 + Pb + 2H_2SO_4 \rightarrow 2PbSO_4 + 2H_2O$$

The sulphuric acid ionizes to produce four positive hydrogen ions (H^+) and two negative sulphate (SO_4^-) ions. A negative charge is developed on the lead plate when an SO_4^- ion combines with the lead plate to form lead sulphate ($PbSO_4$). The positive hydrogen ions (H^+) combine with electrons of the lead-peroxide plate and become neutral hydrogen atoms. They then combine with the oxygen (O) of this plate to become water (H_2O). The lead-peroxide plate, thus, becomes positively charged. A fully charged lead-acid cell has an electrical potential developed between electrodes of approximately 2.0 volts.

After a cell discharges when supplying current to a load for a certain period of time, it is no longer able to develop an output voltage. The cell may then be charged by causing direct current to flow through the cell in the opposite direction. The chemical process is reversed as follows:

$$2PbSO_4 + 2H_2O \rightarrow PbO_2 + Pb + 2H_2SO_4$$

Thus, the original state of the chemicals is reached by the charging action.

Specific Gravity of Secondary Cells

The amount of charge may be measured by a specific-gravity test using a hydrometer to sample the electrolyte. The *specific gravity* of a liquid provides an index of how much heavier than water the liquid is. Pure sulphuric acid has a specific gravity of 1.840, while the dilute sulphuric acid of a fully charged lead-acid cell varies from 1.275 to 1.300. During discharge of a cell, water is formed, reducing the specific gravity of the electrolyte. A specific gravity of between 1.120 and 1.150 indicates a fully discharged cell.

Ampere-Hour Rating of Secondary Cells

The capacity of a battery composed of lead-acid cells is given by an ampere-hour rating. A 60-ampere-hour battery could theoretically deliver 60 amperes for 1 hour, 30 amperes for 2 hours, or 15 amperes for 4 hours. However, this is an approximate rating dependent upon the rate of discharge and the operating temperature of the battery. The normal operating temperature is considered to be 80° Fahrenheit.

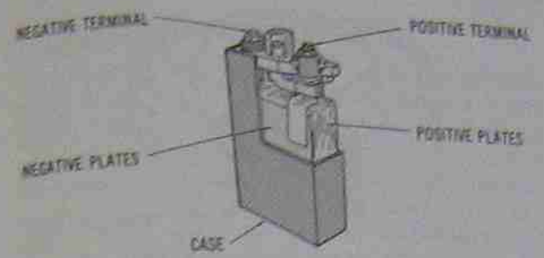


Fig. 5-8. Cutaway drawing of a nickel-iron (Edison) secondary cell.

Nickel-Iron Cells

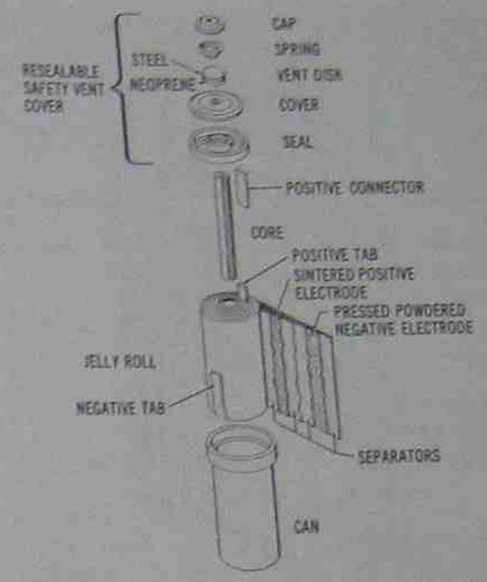
The nickel-iron or "Edison" cell, shown in Fig. 5-8, is a secondary cell constructed with an unbreakable case of welded nickel-plated sheet steel. The positive plate is made of nickel tubes about ⅛ inch in diameter and 4⅛ inches long. Nickel oxide (NiO_2) is contained in the tubes, which are mounted into steel grids and forced into position under high pressure. The positive plates are assembled into groups. The negative plates of the Edison cell are made of flat nickel-plated steel pockets which are composed of iron oxide. They are built into steel grids in groups in the same way as the positive plates. The electrolyte is a solution of potassium hydroxide (KOH) with lithium hydroxide added.

The chemical action of the nickel-oxide cell is very complex as compared to the lead-acid cell; however, they are similar in many respects. The potassium hydroxide electrolyte (KOH) breaks up into negative and positive ions. The negative ions move toward the iron plate, oxidize the iron, and give up excess electrons to the plate. This plate becomes negatively charged. The positive ions move to the nickel-oxide plate and takes electrons from the plate. The deficiency of electrons causes the nickel-oxide plate to become positively charged. The voltage produced by the chemical action of a nickel-iron cell is about 1.4 volts.

The internal resistance of the nickel-iron (Edison) cell is higher than the lead-acid cell. This resistance increases quickly as the cell discharges. Unlike the lead-acid cell, the nickel-iron cell cannot be tested using a hydrometer to show its discharge level. A voltmeter is used to indicate the state of charge of the nickel-iron cell. This cell is also charged by applying a direct-current voltage to the positive and negative terminals and causing current within the cells to flow in reverse. The chemicals are thus reactivated so that the cells may be used again.

Other Types of Secondary Cells

Another type of secondary cell which has gained recent popularity is the nickel-cadmium cell, sometimes



Courtesy Union Carbide Corp.

Fig. 5-9. Exploded view of a small, cylindrical-type, nickel-cadmium secondary cell.

called a "Nicad" battery. These cells are available in large or small sizes with capacities up to 2000 ampere-hours. Fig. 5-9 shows the small rechargeable type of nickel-cadmium cell which is used extensively in portable equipment. A larger nickel-cadmium cell is shown in Fig. 5-10. The positive plate of this cell is nickel hydroxide, the negative plate is cadmium hydroxide, and the electrolyte is potassium hydroxide. These cells are extremely reliable, operate over a wide range of temperatures, and have a long life expectancy. A fully charged nickel-cadmium cell has a voltage of approximately 1.35 volts per cell.

There are a few other types of secondary cells in use today. Most of these types are for specialized applications. Other cells include the silver-oxide-zinc cell and the silver-cadmium cell. These cells have the highest output per physical size and the longest life, but they are more expensive than other cells. One type of "silver" cell is shown in Fig. 5-11.

Applications of Secondary Cells

Secondary cells in the form of storage batteries are used in industry and commercial buildings to provide emergency power in the event of power failure. Such standby systems are necessary to sustain lighting and some critical operations when power is not available. Industrial trucks and loaders use storage batteries for their everyday operation. Many types of instruments

Courtesy McGraw-Edison Co.

Fig. 5-10. A transparent view of a larger nickel-cadmium secondary cell.

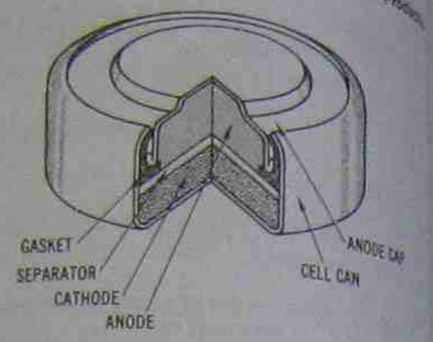
and portable equipment rely upon batteries for power. Several of these instruments get their power from rechargeable secondary cells rather than primary cells. Railway cars use batteries for lighting when they are not in motion. Of course, automotive systems of all kinds use secondary batteries to supply direct-current power for starting and lighting.

DIRECT-CURRENT GENERATING SYSTEMS

Mechanical generators are used in many situations to produce direct current. These generators convert mechanical energy into direct-current electrical energy.

Construction of DC Generators

The parts of a simple direct-current generator are shown in Fig. 5-12. The principle of operation of a direct-current generator is similar to that of the alternating-current generator which was discussed previously. A rotating armature coil passes through a magnetic field that is developed between the north and south polarities of permanent magnets or electromagnets. As the coil rotates, electromagnetic induction causes a current to be induced into the coil. The current produced is an *alternating current*. However, it is possible to convert the alternating current which is induced into the armature into a form of direct cur-



Courtesy Union Carbide Corp.

Fig. 5-11. Cutaway drawing of a silver-oxide-zinc secondary cell.

rent. The conversion of ac to dc is accomplished through the use of a *split-ring commutator*. The conductors of the armature of a direct-current generator are connected to split-ring commutator segments. The split-ring commutator shown in Fig. 5-12 has two segments which are insulated from one another and from the shaft of the machine on which it rotates. An end of each armature conductor is connected to each commutator segment. The purpose of the split-ring commutator is to reverse the armature-coil connection to the external load circuit at the same time that the current induced in the armature coil reverses. This causes direct current of the correct polarity to be applied to the load at all times.

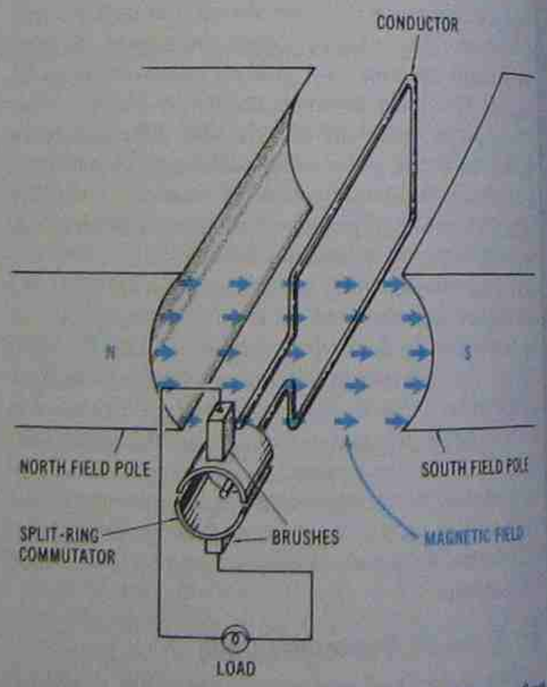
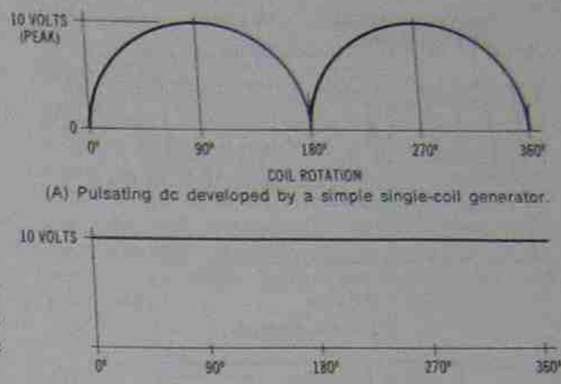


Fig. 5-12. Simplified drawing of the basic parts of a direct-current generator.

Voltage Output of DC Generators

The voltage developed by the single-coil generator shown in Fig. 5-12 would appear as illustrated in Fig. 5-13A. This pulsating direct current is not suitable for most applications. However, by using many turns of wire around the armature and several split-ring commutator segments, the voltage developed can be a smooth direct current such as that produced by a battery. This type of output is shown in Fig. 5-13B. The voltage developed by a direct-current generator depends upon the strength of the magnetic field, the number of coils in the armature, and the speed of rotation of the armature. By increasing any of these factors, the voltage output can be increased.



(A) Pulsating dc developed by a simple single-coil generator.

(B) Pure dc developed by a more complex generator using many turns of wire and many commutator segments.

Fig. 5-13. Output waveforms of direct-current generators.

Types of Direct-Current Generators

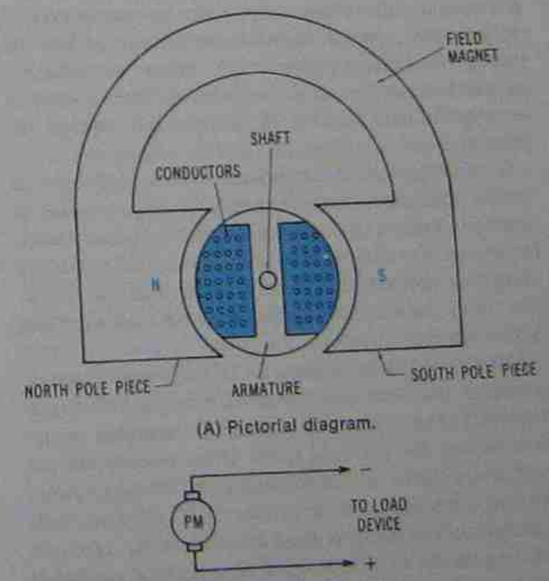
Direct-current generators are classified according to the way in which a magnetic field is developed in the stator of the machine. One method is to use a permanent-magnet field. It is also possible to use electromagnets to develop a magnetic field by applying a separate source of direct current to the electromagnetic coils. However, the most common method of developing a magnetic field is for part of the generator output to be used to supply direct-current power to the field of the machine. Thus, there are three basic classifications of direct-current generators: (1) permanent magnet field, (2) separately excited field, and (3) self-excited field. The self-excited types are further subdivided according to the method used to connect the armature windings to the field circuit. This can be accomplished by the following connection methods: (1) series, (2) parallel (shunt), or (3) compound.

Permanent-Magnet DC Generator—A simplified diagram of a permanent-magnet dc generator is shown in Fig. 5-14. The conductors shown in this diagram are connected to the split-ring commutator and brush assembly of the machine. The magnetic field is established by using permanent magnets made of Alnico (an alloy of aluminum, nickel, cobalt, and iron) or some other natural magnetic material. It is possible to group several permanent magnets together to create a stronger magnetic field.

The armature of the permanent-magnet dc generator consists of many turns of insulated conductors. Therefore, when the armature rotates within the permanent-magnetic field, an induced voltage is developed that can be applied to a load circuit. Applications for this type of dc generator are usually confined to those which require low amounts of power. A magneto is an example of a permanent-magnet dc generator.

Separately Excited DC Generator—Where large amounts of direct-current electrical energy are needed, generators with electromagnetic fields are used. Stronger fields can be produced by electromagnets. It is possible to control the strength of the electromagnetic field by varying the current through the field coils. The output voltage of generators which use electromagnetic fields can be controlled with ease.

The direct current used to establish the electromagnetic field is referred to as the excitation current. When dc excitation current is obtained from a source separate from the generator, it is called a *separately excited* dc generator. This type of generator is shown in Fig. 5-15.



(A) Pictorial diagram.

(B) Schematic diagram.

Fig. 5-14. Simplified drawing of a permanent-magnet direct-current generator.

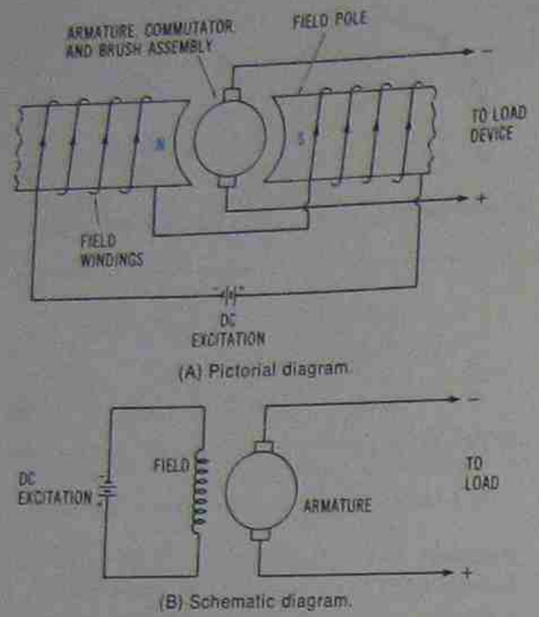


Fig. 5-15. Simplified illustration of a separately excited direct-current generator.

Storage batteries are often used to supply the dc excitation current to this type of generator. The field current is independent of the armature current. Therefore, the separately excited generator maintains a very stable output voltage. Changes in load of the external circuit affect the armature current but do not vary the strength of the field. The voltage output of a separately excited dc generator can be varied by adjusting the current through the field. A high-wattage rheostat (variable resistance) connected in series with the field coils will accomplish field control of a sepaartely excited dc generator.

Separately excited dc generators are used only in certain applications where precise voltage control is essential. Automatic control processes in industry often require such precision. However, the cost of separately excited dc generators is usually prohibitive and, therefore, other means of obtaining direct-current electrical power are used.

Self-Excited Series-Wound DC Generators—Since dc generators produce direct current, it is possible to extract part of the output of a generator to obtain excitation current for the field coils. Generators which use part of their own output to supply the exciting current for the electromagnetic field are called *self-excited* dc generators. The method used to connect the armature windings to the field windings determines the characteristics of the generator. It is possible to connect armature and field windings in series, parallel (shunt), or series-parallel (compound).

The self-excited series-wound dc generator has a armature windings connected in series with the fie coils and the load circuit as shown in Fig. 5-16. In th generator, the total current flowing through the loa also flows through the field coils. The field coils are therefore, wound using only a few turns of low-resis tance large-diameter wire. A sufficient electromagneti field can then be produced by the large current flowing through the coils.

If the load circuit is disconnected, no current flows through the generator. However, the field coils retain a small amount of magnetism known as *residual magnetism*. Due to residual magnetism, a current will begin to flow through the generator and the load circuit when a load circuit is connected. The current will continue to increase, thus causing an increase in the magnetic strength of the field. The output voltage rises proportionally with increases in current flow through the load and generator circuits. The output curve of a series-wound dc generator is shown in Fig. 5-17. The peak of the curve is reached when magnetic saturation of the field occurs. Magnetic saturation prohibits any increase in output voltage. After saturation is reached, any increase in load current causes a rapid decline in the output voltage due to circuit losses.

The output voltage of a self-excited series-wound dc generator varies appreciably with changes in load current. However, beyond the peak of its output curve the load current remains fairly stable with large variations in voltage. There are specific applications, such as arc welding, that require stable load current as the

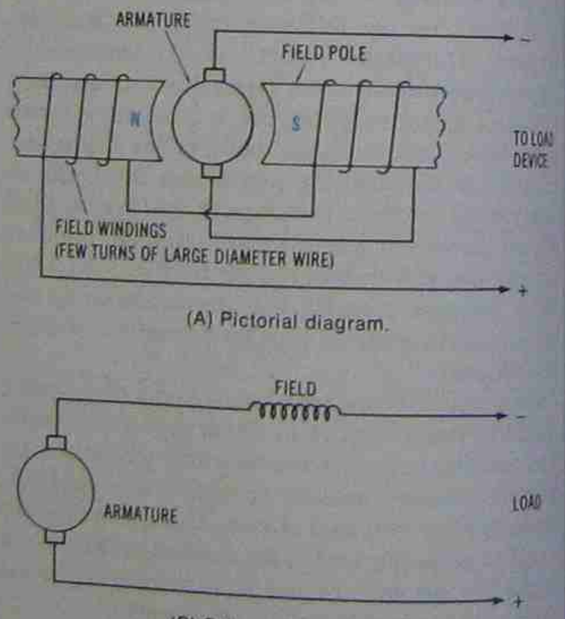


Fig. 5-16. Simplified illustration of a self-excited, series-wound dc generator.

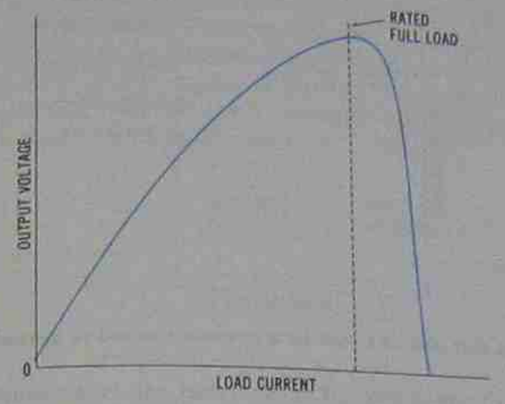


Fig. 5-17. The output curve of a series-wound dc generator.

voltage changes. However, the self-excited series-wound generator has very few applications.

Self-Excited Shunt-Wound DC Generator—By connecting the field coils, the armature circuit, and the load circuit in parallel, a shunt-wound dc generator configuration is obtained. Fig. 5-18 shows this type of generator. The output current developed by the generator (I_A) has one path through the load circuit (I_L) and another through the field coils (I_F). The generator is usually designed so that the field current is not more than 5% of the total armature current (I_A).

In order to establish a strong electromagnetic field and to limit the amount of field current, the field coils are wound with many turns of small diameter wire. These high-resistance coils develop a strong field due to the number of turns and, therefore, rely very little on the amount of field current to develop a strong magnetic field.

With no load circuit connected to the shunt-wound dc generator, an induced voltage is produced as the armature rotates through the electromagnetic field. Again, the presence of residual magnetism in the field coils is critical to the operation of the machine. A current flows in the armature and field circuit as long as there is residual magnetism. As the generated current increases, the output voltage also increases up to a peak level.

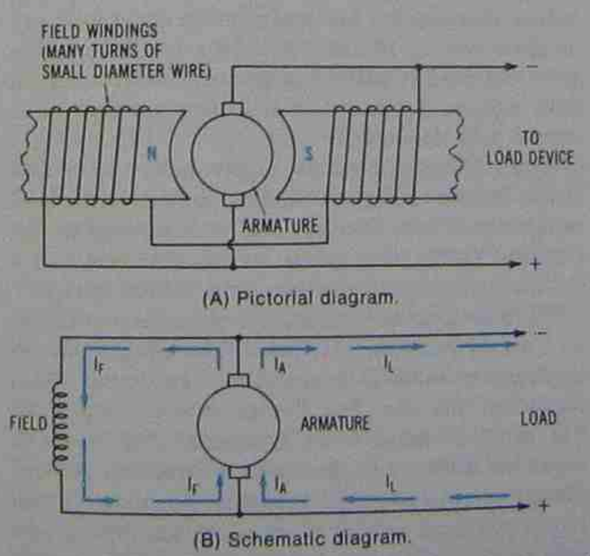


Fig. 5-18. Simplified illustration of a self-excited, shunt-wound dc generator.

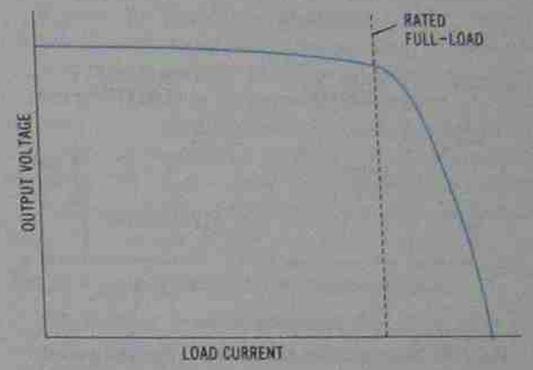
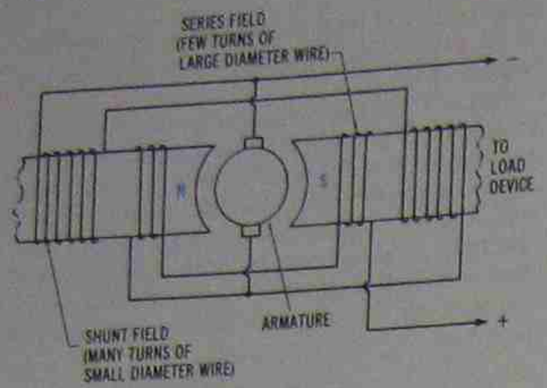


Fig. 5-19. Output curve of a shunt-wound dc generator.

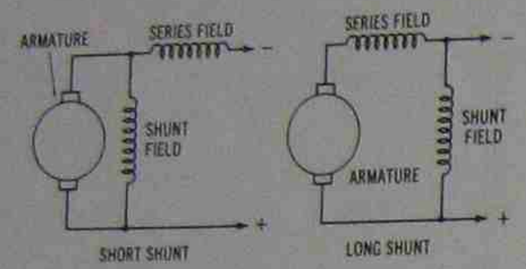
When a load circuit is connected to the shunt generator, the armature current (I_A) increases due to the additional parallel path. This, then, will increase the $I \times R$ drop in the armature, resulting in a smaller output voltage. Further increases in load current cause corresponding decreases in output voltage as shown in the output curve of Fig. 5-19. With small load currents, the output voltage is nearly constant as load current varies. A large load causes the armature current to decrease. This decrease is desirable because, in case of a short circuit, the generator has a built-in protective feature.

The self-excited shunt-wound dc generator is used where a constant output voltage characteristic is needed. It may be used to supply excitation current to a large ac generator or to charge storage batteries. However, in applications when initial expense is not critical, the compound-wound generator described next may be more desirable.

Self-Excited Compound-Wound DC Generator—The compound-wound dc generator has two sets of field windings. One set is made of low-resistance windings and is connected in series with the armature circuit. The other set is made of high-resistance wire and is connected in parallel with the armature circuit. A compound-wound dc generator is illustrated in Fig. 5-20.



(A) Pictorial diagram.



(B) Schematic diagram.

Fig. 5-20. Simplified illustration of a compound-wound dc generator.

As discussed previously, the output voltage of a series-wound dc generator increases with an increase in load current, while the output voltage of a shunt-wound dc generator decreases with an increase in load current. It is possible to produce a dc compound-wound generator, utilizing both series and shunt windings, that has an almost constant voltage output under changing loads. A constant voltage output can be obtained with varying loads if the series field windings have the proper characteristics to set up a sufficient magnetic field to counterbalance the voltage reduction caused by the $I \times R$ drop in the armature circuit.

A constant output voltage is produced by a *flat-compounded* dc generator. The no-load voltage is equal to the rated full-load voltage in this type of machine, as shown by the output curves of Fig. 5-21. If the series windings produce a stronger field, the generator will possess a series characteristic. The voltage output will increase with an increase in load. A compound-wound generator whose full-load voltage is greater than its no-load voltage is called an *overcompounded* dc generator. Likewise, if the shunt windings produce a stronger field, the output will be more characteristic of a shunt generator. Such a generator, whose full-load voltage is less than its no-load voltage, is called an *undercompounded* dc generator.

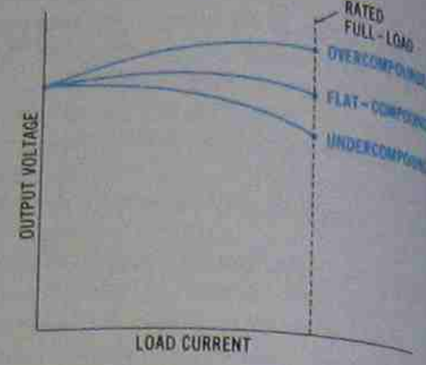


Fig. 5-21. Output curves for a compound-wound dc genera

Compound-wound dc generators can be constru so that the series and shunt fields either aid or opp one another. If the magnetic polarity of adjacent fi are the same, the magnetic fields aid each other and i said to be *cumulatively* wound. Opposing polarities adjacent coils produce a *differentially* wound machi For almost all applications of compound-wound m chines, the cumulative-wound method is used. A ge erator wound in this way maintains a fairly consta voltage output with variations in load current. Th compound-wound dc generator is used more extensiv than other dc generators due to its constant voltag output and its design flexibility to obtain various outp characteristics.

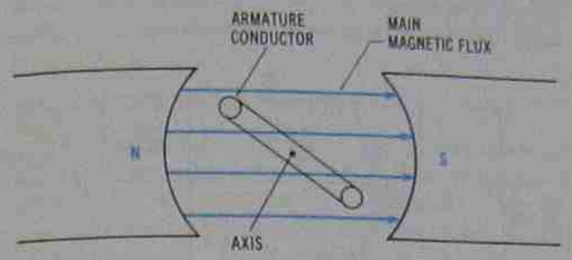
Common DC Generator Characteristics

Direct-current generators are used primarily for p eration with mobile equipment. In industrial plants a commercial buildings, they are used for standby pow battery charging, and for specialized dc operations su as electroplating. In many situations, rectification sy tems that convert alternating current to direct curre have replaced dc generators since they are cheaper t operate and maintain.

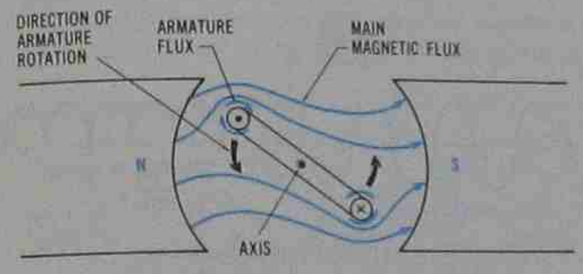
Direct-current generators supply power to a loa circuit by converting the mechanical energy of som prime mover, such as a gasoline or diesel engine, int electrical energy. The prime mover must rotate at definite speed in order to produce the desired voltage.

When dc generators operate, a characteristic known as *armature reaction* takes place. The current through the armature windings produces a magnetic flux which reacts with the main field flux as shown in Fig. 5-22. The result is that a force is created which tends to rotate the armature in the opposite direction. As load current increases, the increase in armature current causes a greater amount of armature reaction to take place. This condition can cause a considerable amount of sparking between the brushes and the commutator.

However, armature reaction may be reduced by placing windings called *interpoles* between the main field windings of the stator. These windings are connected in series with the armature windings. Thus, an increase in armature current creates a stronger magnetic field around the interpoles which counteracts the main field distortion created by the armature conductors.



(A) Main magnetic flux with no current in the armature windings.



NOTE: Indicates electron flow toward the observer, and a clockwise magnetic flux.

Indicates electron flow away from the observer, and a counterclockwise magnetic flux.

(B) Distortion of main magnetic flux with current in the armature windings.

Fig. 5-22. Illustration of armature reaction.

Rating of DC Generators—The output of a dc generator is usually rated in kilowatts, which is the electrical power capacity of a machine. Other ratings, which are specified by the manufacturer on the nameplate of the machine, are current capacity, output voltage, speed, and temperature. Direct-current generators are made in a wide range of physical sizes and with various electrical characteristics.

DC Generator Applications—Direct-current generator use has declined rapidly since the development of the low-cost silicon rectifier. However, there are still certain applications where dc generators are used. These applications include railroad power systems, synchronous motor-generator units, power systems for large earth-moving equipment, and dc motor-drive units for precise equipment control.

DIRECT-CURRENT CONVERSION SYSTEMS

Most of the electrical power produced is 60-Hz three-phase alternating current. However, the use of direct current is necessary for many applications. For instance, dc motors have more desirable speed-control and torque characteristics than ac motors. We have already discussed two methods of supplying direct current—batteries and dc generators. The fact that batteries and dc generators have been used as direct-current power sources for many years has been discussed. In many cases today, where large amounts of direct-current power are required, it is more economical to use a system for converting alternating current to direct current. Direct-current load devices may be powered by systems, called either *rectifiers* or *converters*, which change alternating current into a suitable form of direct current. Some types of ac-dc conversion systems include (1) semiconductor rectifiers, (2) vacuum-tube rectifiers, (3) gaseous-tube rectifiers, and (4) rotary converters. Semiconductor rectifiers are used much more than the other types.

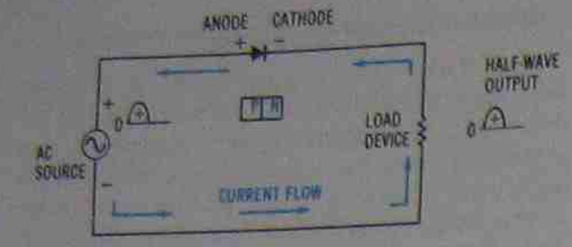
Single-Phase Rectification Systems

The simplest system for converting alternating current to direct current is single-phase rectification. A single-phase rectifier changes alternating current to pulsating direct current. Rectification can be accomplished by using either semiconductors, vacuum tubes, gaseous tubes, or rotary converters. The most common and economical method is the use of low-cost silicon semiconductor rectifiers.

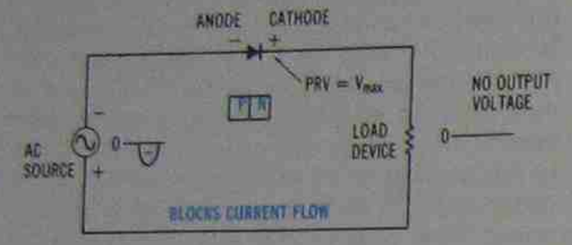
Single-Phase Half-Wave Rectification

A single-phase half-wave rectifier circuit, such as shown in Fig. 5-23, converts an alternating-current source voltage into a pulsating direct current. Let us assume that during the positive alternation of the ac cycle, the anode of the diode is positive (Fig. 5-23A). The diode will then conduct since it is forward biased and the pn junction is low resistant. The positive half cycle of the alternating current will then appear across the load device (represented by a resistor).

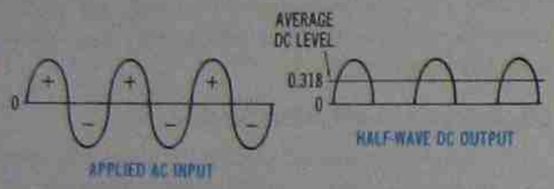
When the negative portion of the ac alternation is input to the circuit, the anode of the diode becomes negative. The diode is now reverse biased and no significant current will flow through the load device (Fig. 5-23B). Therefore, there will be no voltage across the load. The input and resulting output waveforms of the half-wave rectifier circuit are shown in Fig. 5-23C. The pulsating direct current of the output has an average dc level. The average value of the pulsating direct current produced by single-phase half-wave rectification is expressed as:



(A) Forward-biased diode.



(B) Reverse-biased diode.



(C) Input/output voltage waveforms.

Fig. 5-23. Single-phase half-wave rectification.

$$V_{dc} = 0.318 \times V_{max}$$

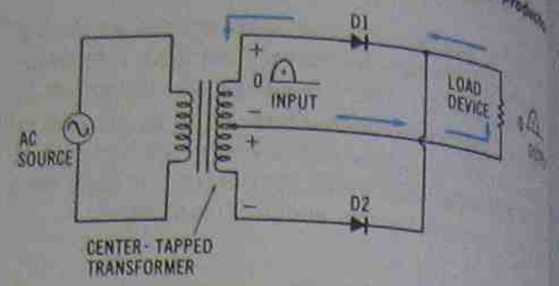
where,

V_{dc} is the average value of rectified voltage,
V_{max} is the peak (maximum) value of applied ac voltage.

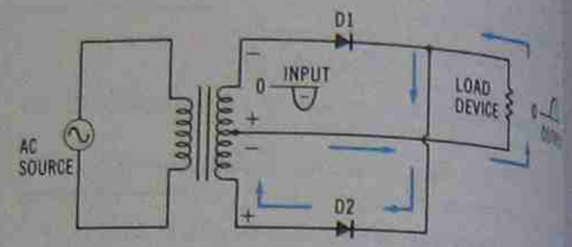
Certain diode ratings should be considered for half-wave rectifier circuits. The maximum forward current (I_{max}) is the largest current that can flow through the diode while it is forward biased without damaging the device. The peak inverse voltage (piv) is the maximum voltage across the diode while it is reverse biased. For the half-wave rectifier, the maximum voltage developed across the diode is V_{max} of the applied ac. As shown in the preceding formula, the piv of a diode used in a half-wave circuit must be much larger than the dc voltage developed.

Single-Phase Full-Wave Rectification

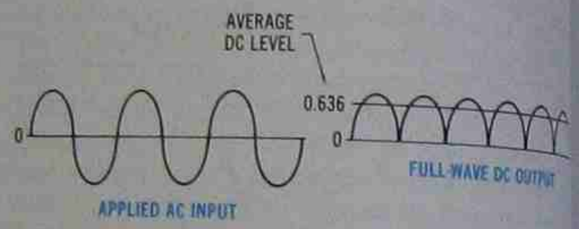
In order to obtain a more pure form of direct-current energy, it is possible to improve upon half-wave rectification systems. Fig. 5-24 shows a single-phase full-wave rectifier that uses two diodes and produces a dc output voltage during each alternation of the ac input. The rectified output of the full-wave rectifier has twice the dc voltage level of the half-wave rectifier.



(A) Diode D1 is forward biased.



(B) Diode D2 is forward biased.



(C) Input/output voltage waveforms.

Fig. 5-24. Single-phase full-wave rectification.

The full-wave rectifier utilizes a center-tapped transformer to transfer ac source voltage to the diode rectifier circuit. During the positive half-cycle of ac source voltage, the instantaneous charges on the transformer secondary are as shown in Fig. 5-24A. The peak voltage (V_{max}) is developed across each half of the transformer secondary. At this time, diode D1 is forward biased and diode D2 is reverse biased. Therefore, conduction occurs from the center-tap, through the load device, through D1, and back to the outer terminal of the transformer secondary. The positive half-cycle is developed across the load as shown.

During the negative half-cycle of the ac source voltage, diode D1 is reverse biased and diode D2 is forward biased by the instantaneous charges shown in Fig. 5-24B. The current path is from the center-tap, through the load device, through D2, and back to the outer terminal of the transformer secondary. The negative half-cycle is also produced across the load, developing a full-wave output as illustrated in Fig. 5-24C.

Each diode in a full-wave rectifier circuit must have a piv rating of twice the value of the peak voltage developed at the output, since twice the peak voltage

($2V_{max}$) is present across the diode when it is reverse biased. The average voltage for a full-wave rectifier circuit is:

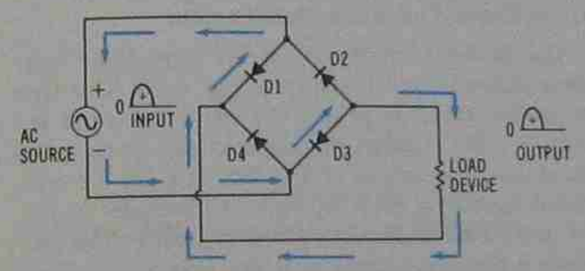
$$V_{dc} = 2\ (0.318 \times V_{max})$$
$$= 0.636 \times V_{max}.$$

This type of rectifier circuit produces twice the dc voltage output of a half-wave rectifier circuit. However, it requires a bulky center-tapped transformer as well as diodes that have a piv rating of twice the peak value of applied ac voltage.

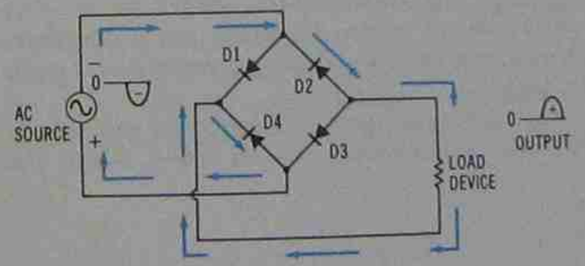
Single-Phase Bridge Rectification

One disadvantage of the full-wave rectifier discussed previously is the requirement for a large center-tapped transformer. To overcome this disadvantage, four diodes may be used to form a full-wave bridge rectifier as shown in Fig. 5-25. Additionally, the diode piv rating is only required to be the peak output-voltage value (V_{max}).

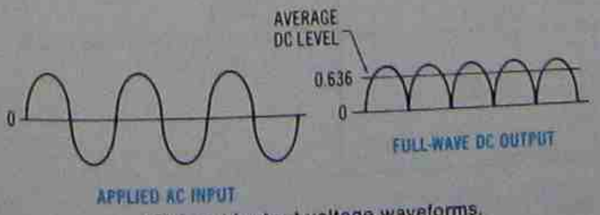
During the operation of a bridge rectifier, two diodes are forward biased during each alternation of the ac input. When the positive half-cycle occurs, as shown in Fig. 5-25A, diodes D1 and D3 are forward biased while diodes D2 and D4 are reverse biased. This biasing condition is due to the instantaneous charges occurring during the positive alternation. The conduction path is from the instantaneous negative side of the ac source, through diode D3, through the load device, through diode D1, and back to the instantaneous positive side of the ac source.



(A) Diodes D1 and D3 are forward biased.



(B) Diodes D2 and D4 are forward biased.



(C) Input/output voltage waveforms.

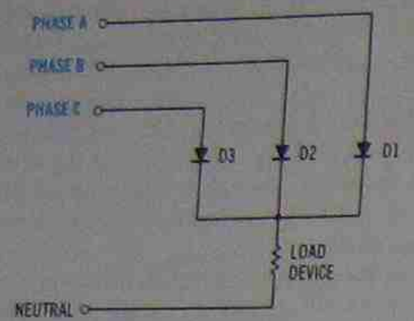
Fig. 5-25. Single-phase full-wave bridge rectification.

During the negative alternation of the ac input, diodes D2 and D4 are forward biased, while diodes D1 and D3 are reverse biased. Conduction occurs, as shown in Fig. 5-25B, from the instantaneous negative side of the source, through diode D2, through the load device, through diode D4, and back to the instantaneous positive side of the ac source. Since a voltage is developed across the load device during both half-cycles of the ac input, a full-wave output is produced, as shown in Fig. 5-25C, that is similar to that of the full-wave rectifier discussed previously. For high values of dc output voltage, the use of a bridge rectifier is desirable since the diode piv rating is one-half that of other single-phase rectification methods.

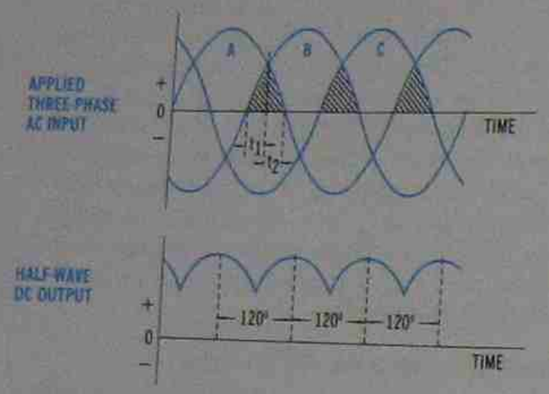
Three-Phase Half-Wave Rectification

Most industries are supplied with three-phase alternating current. It is therefore beneficial, due to the inherent advantages of three-phase power, to use three-phase rectifiers to supply dc voltage for industrial use. Single-phase rectifiers are ordinarily used where low amounts of dc power are required. To supply larger amounts of dc power for industrial requirements, a three-phase rectifier circuit, such as the one shown in Fig. 5-26, could be employed. Three-phase rectifier circuits produce a purer dc voltage output than single-phase rectifier circuits, thus wasting less ac power.

Fig. 5-26 shows a three-phase half-wave rectifier circuit which does not use a transformer. Phases A, B, and C of the wye-connected three-phase source supply voltage to the anodes of diodes D1, D2, and D3. The load device is connected between the cathodes of the diodes and the neutral point of the wye-connected source. Maximum conduction occurs through diode D1, since it is forward biased, when phase A is at its peak positive value. No conduction occurs through diode D1 during the negative alternation of phase A. The other diodes operate in a similar manner, conducting during the positive ac-input alternation and not conducting during the associated negative ac alternation. In a sense, this circuit combines three single-phase half-wave rectifiers to produce a half-wave dc output, as shown in Fig. 5-26B. Of course, the voltages appearing across the diodes are 120° out of phase. There is a period of time during each ac cycle when the positive alternations



(A) Schematic diagram.



(B) Input/output voltage waveforms.

Fig. 5-26. Three-phase half-wave rectification.

overlap one another as shown in the shaded areas of the diagram (Fig. 5-26B). During the overlap time period t_1, the phase A voltage is more positive than the phase B voltage, while during the t_2 interval, the phase B is more positive. Diode D1 will conduct until the time period t_1 ends, then diode D2 will conduct beginning at the end of t_1 until the next area of overlapping is reached.

Note that voltage across the load device rises to a peak value twice during each phase alternation of the ac input voltage. These peaks are 120° apart. Since the dc output voltage never falls to zero, less ac ripple is present, which results in a purer form of dc than single-phase rectifiers produce. The average dc output voltage (V_{dc}) is expressed as:

$$V_{dc} = 0.831 \times V_{max},$$

which compares very favorably with single-phase full-wave rectifier circuits.

A disadvantage of this type of three-phase rectifier is that the ac lines are not isolated. The lack of isolation, which is a direct connection to the ac lines, could be a hazardous safety factor. To overcome this disadvantage, a transformer may be used, as shown in Fig. 5-27, to form a similar three-phase half-wave rectifier. The secondary voltage may be either increased or decreased by the proper selection of the transformer, providing a variable dc voltage capability. The circuit illustrated has a delta-to-wye–connected transformer. The operation of this circuit is identical to that of the three-phase half-wave rectifier previously discussed; however, load isolation has been accomplished.

Three-Phase Full-Wave Rectification

The full-wave counterpart of the three-phase half-wave rectifier circuit is shown in Fig. 5-28. This type of rectifier circuit is popular for many industrial applications. Six rectifiers are required for operation of the circuit. The anodes of D4, D5, and D6 are connected together at point A, while the cathodes of D1, D2, and D3 are connected together at point B. The load device is connected across these two points. The three-phase ac lines are connected to the anode-cathode junctions of D1 and D4, D2 and D5, and D3 and D6. This circuit does not require the neutral line of the three-phase source; therefore, a delta-connected source could be used.

The resulting dc output voltage of the three-phase full-wave rectifier circuit is shown in Fig. 5-28B. The

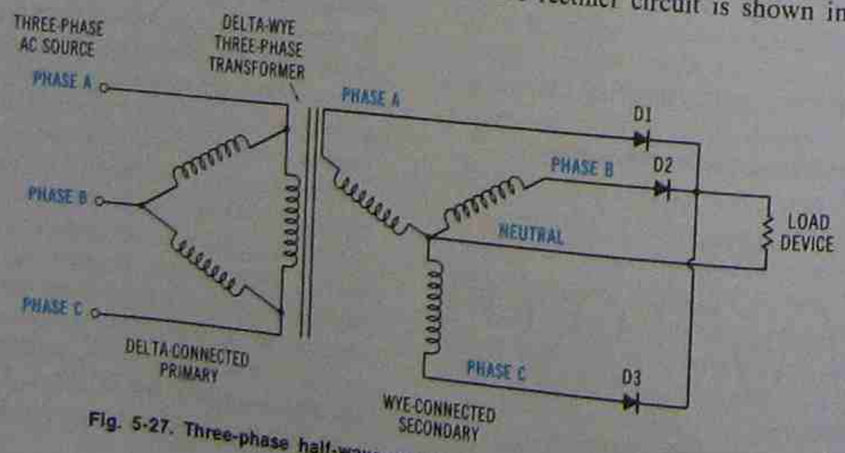
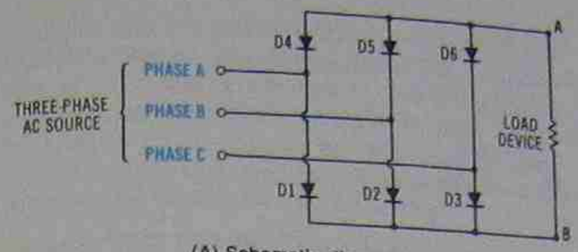
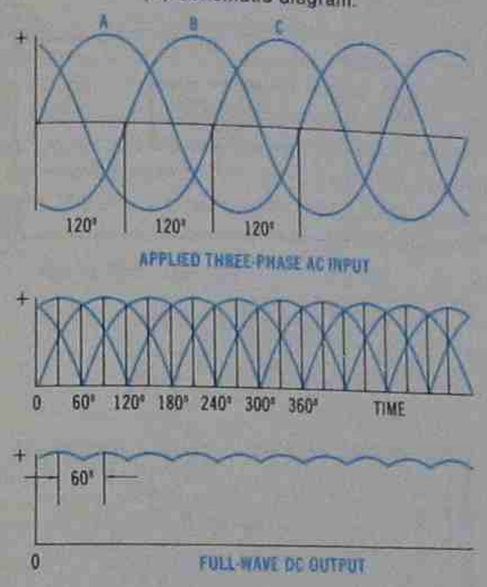


Fig. 5-27. Three-phase half-wave rectification using a transformer.



(A) Schematic diagram.



(B) Input/output voltage waveforms.

Fig. 5-28. Three-phase full-wave rectification.

operation of the circuit is similar to a single-phase bridge rectifier in many respects. At any single instant of time along the three-phase ac input cycle, the anode voltage of one of the diodes is more positive than all the others, while the cathode voltage of another diode is more negative than all the others. These two diodes will then form the conduction path for that time period. This conducting action is similar to a bridge rectifier, since two diodes conduct during a time interval. Each rectifier in this circuit conducts during one-third of an ac cycle (120°). Peak positive dc output voltage occurs during every 60° of the three-phase ac input.

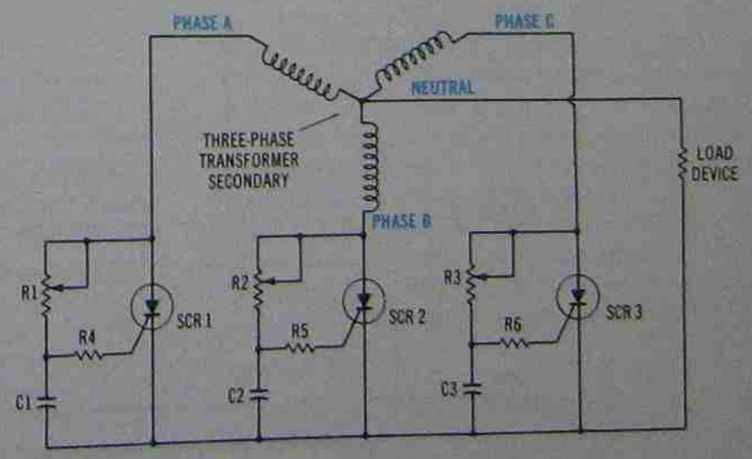
Three-Phase Rectification Using SCRs

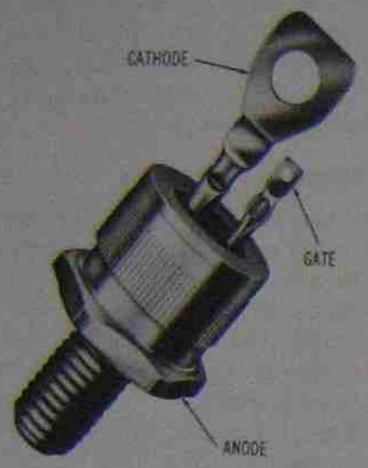
The rectification circuits previously discussed have no means of controlling the output voltage and current levels. In the circuit shown in Fig. 5-29, silicon controlled rectifiers (SCRs) are used in place of semiconductor diode rectifiers. The conduction time of a silicon controlled rectifier can be varied to control dc output voltage and current levels.

The use of an SCR as a controlled rectifying device may be observed by referring to Fig. 5-30. The SCR conducts when its forward breakover voltage (V_{BO}) is reached. This V_{BO} is determined by the gate control voltage level. When the SCR conducts, current flows through the load device as shown in Fig. 5-30D. When the ac source voltage level drops to that shown at point 2 of Fig. 5-30E (holding current level), the SCR turns off and remains off during the negative half-cycle of ac input. Voltage is developed across the load only from point 1 to point 2 on Fig. 5-30E. When the gate control circuit (Fig. 5-30C) is used to change the V_{BO} value, the result is to change conduction time of the SCR as shown by the dotted lines in Fig. 5-30E. The dotted lines illustrate the effect of a reduced V_{BO} on anode-cathode voltage of the SCR and the corresponding voltage developed across the load. Similar rectifying action may be accomplished by using gaseous thyratron tubes in place of SCRs.

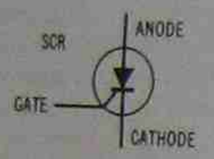
In order to control the conduction time of the SCRs of the three-phase rectifier (Fig. 5-29), a phase-shift network is used. In Fig. 5-29, R1–C1, R2–C2, and R3–C3 are identical RC phase-shifting circuits. The

Fig. 5-29. Three-phase rectification using SCRs.

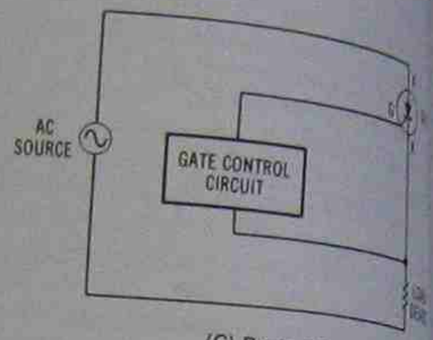




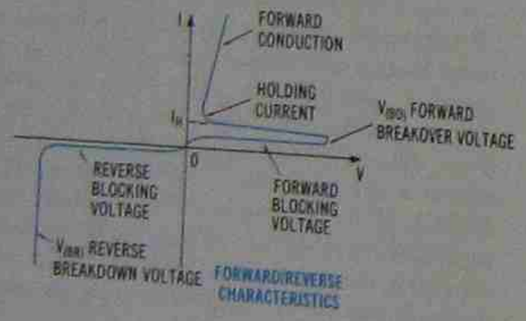
(A) Physical appearance.



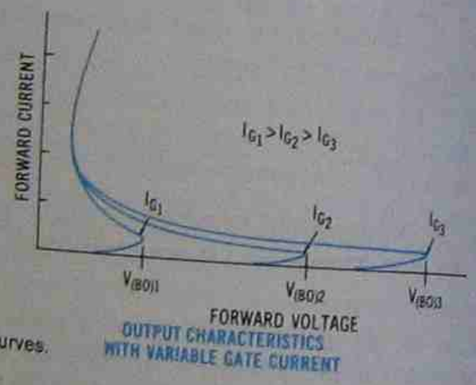
(B) Schematic symbol.

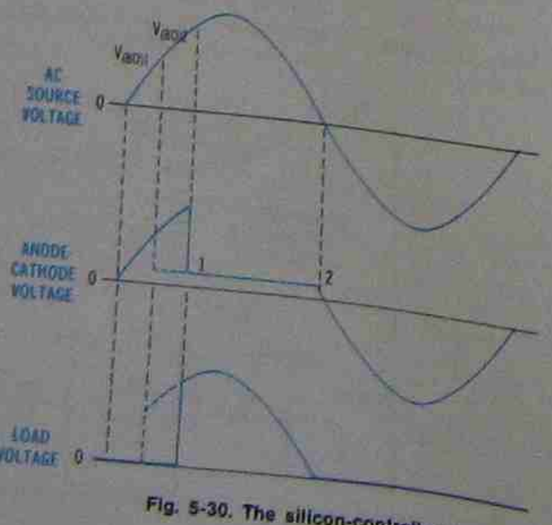


(C) Basic SCR circuit.



(D) SCR characteristic curves.





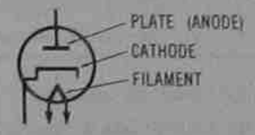
(E) SCR waveform relationships.

Fig. 5-30. The silicon-controlled rectifier.

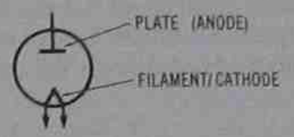
three rheostats are ganged together to accomplish control by varying one rheostat adjustment. The conduction time of the circuit is increased by increasing the resistance of the rheostats. Operationally, this circuit is the same as the three-phase half-wave rectifier previously discussed. However, the dc output may be easily controlled by varying the rheostat setting.

Vacuum-Tube and Gaseous-Tube Rectifiers

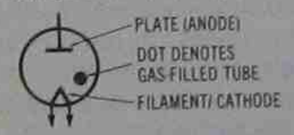
For many years, industries have been concerned with the electronic control of industrial equipment and processes. There are still methods other than semiconductor rectifier circuits which are used to supply direct-current power. In some cases, semiconductors are limited by the amount of current they are capable of handling. Where control of extremely large amounts of current is required, vacuum-tube or gaseous-tube rectifiers may be used.



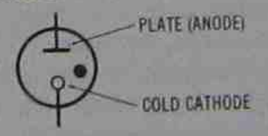
(A) Vacuum-tube diode, indirectly heated cathode.



(B) Vacuum-tube diode, directly heated cathode.



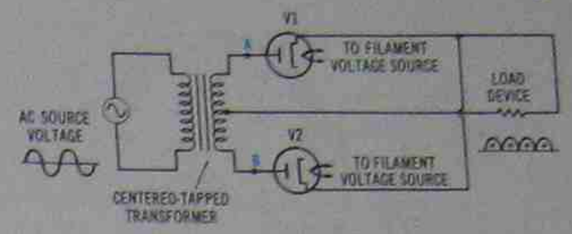
(C) Gaseous-tube diode, "hot" cathode.



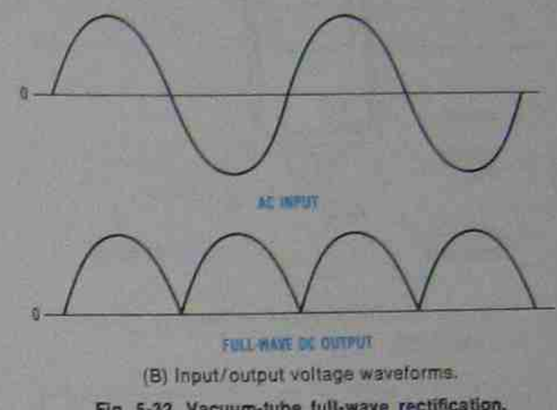
(D) Gaseous-tube diode, "cold" cathode (glow-tube).

Fig. 5-31. Vacuum-tube and gaseous-tube diodes.

Vacuum-tube diodes, whose symbols are shown in Figs. 5-31A and 5-31B, consist of a filament cathode and plate (or anode). The filament must be heated by the application of an electrical potential, usually alternating current. A vacuum-tube–diode full-wave rectifier circuit is shown in Fig. 5-32. Compare this circuit with its semiconductor counterpart of Fig. 5-24. A vacuum tube will conduct only when its plate is made positive relative to its cathode. Tube V1 will conduct when point A is positive and tube V2 will conduct when



(A) Schematic diagram.



(B) Input/output voltage waveforms.

Fig. 5-32. Vacuum-tube full-wave rectification.

point B becomes positive. A full-wave output will appear across the load device.

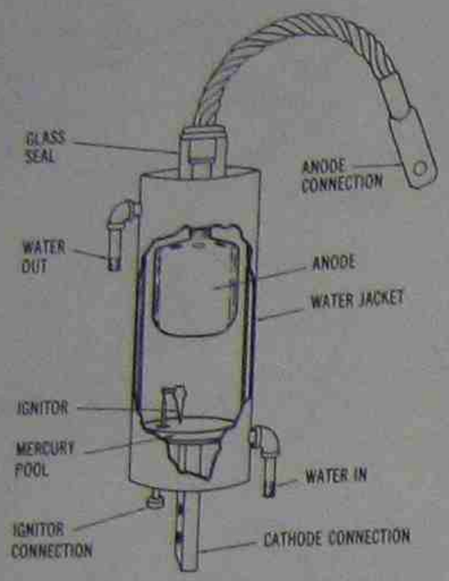
One problem of the vacuum-tube diode is that not all of the electrons which are emitted by the cathode reach the plate. The ionization which takes place in a gaseous-tube diode overcomes this undesirable aspect of vacuum-tube diodes. Thus, an increased amount of current can be conducted using a gaseous-tube diode. An example of a gaseous-tube rectifier circuit would be one that is identical to the vacuum-tube circuit shown in Fig. 5-32A but with gaseous-tube diodes substituted for the vacuum tubes.

Glow-Tube Rectifier

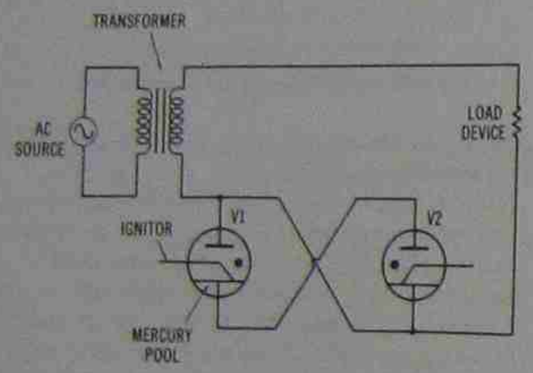
Another type of gaseous-tube rectifier is known as a *glow-tube*. This device has an unheated (or "cold") cathode (Fig. 5-31D). When a high enough potential is applied to the plate of a glow tube, ionization will take place. Ionization of the gas within the tube causes a visible glow to result. The advantage of this type of tube is that the voltage drop across the tube remains fairly constant over a large range of plate-current values. Thus, the primary use of the glow tube has been for voltage regulation circuits where a constant voltage over a wide range of load currents is desirable.

Ignitron Rectifier

Another gaseous tube, which is used to handle up to 10,000 amperes of current, is called an *ignitron*. Ig-



(A) Cutaway drawing.

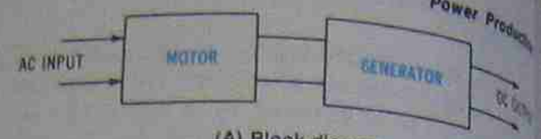


(B) Circuit diagram.

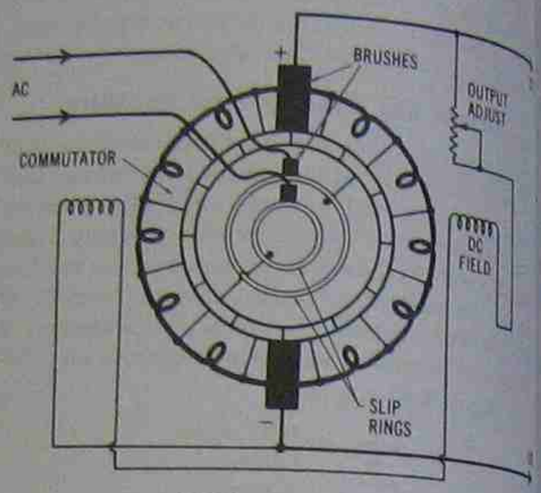
Fig. 5-33. The ignitron tube.

nitrons are usually connected in pairs as shown in Fig. 5-33. The ability of ignitrons to handle extremely large currents makes them suitable for use in electronic welder circuits.

The ignitron is a gaseous tube which is not heated, but uses a pool of liquid mercury as its cathode. If some means are used to establish an arc within the ignitron, a large quantity of electrons will be attracted to its anode when a positive charge is placed on it. The ignitor of the tube extends to near the mercury pool (see Fig. 5-33A). When a positive potential of a high enough value is applied to the ignitor, an arc is started between it and the mercury pool. Electrons are then passed to the anode due to the ionization that takes place. When current flows through the tube, the ignitor arc is no longer needed, so it is stopped. A thryatron or saturable reactor circuit could be used to control



(A) Block diagram.



(B) Schematic diagram.

Fig. 5-34. Rotary ac-to-dc converter.

ignitor firing. The high current flowing in an ignitron tube causes a great deal of heat to be produced. Ordinarily, water is circulated through the tube to remove this heat.

Rotary Converters

Another method which has been used to convert alternating current to direct current is by use of a *rotary converter*. Rotating ac-to-dc converters are seldom used today. However, motor-driven generator units, such as the one shown schematically in Fig. 5-34, can also be used to convert direct current to alternating current. This system is called an *inverter*. When operated as a converter to produce dc, the machine is run off an ac line. The ac is transferred to the machine windings through slip rings and converted to dc by a split-ring commutator located on the same shaft. The amount of dc voltage output is determined by the magnitude of the ac voltage applied to the machine. Converters may be designed as two units, with motor and generator shafts coupled together, or as one unit housing both the motor and generator.

DIRECT-CURRENT FILTERING METHODS

The pulsating direct-current produced by both single-phase and three-phase rectifier circuits is not pure direct current. A certain amount of alternating-current ripple is evident in each type of rectifier. For many applications, a smooth dc output voltage with the ac

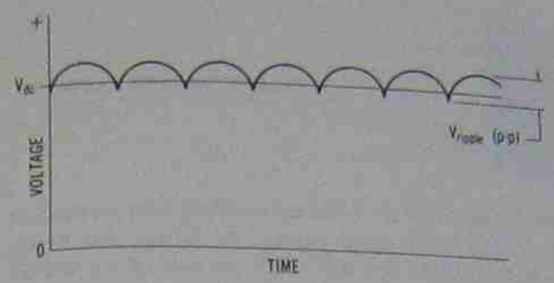


Fig. 5-35. Rectifier output voltage.

ripple removed is required. Circuits used to remove ac variations of rectified direct current are called *filter circuits*.

The output of a rectifier has a dc value and an ac ripple value as shown in Fig. 5-35. To gain a relative index of the amount of ac variation, the ripple factor of a rectifier output waveform may be determined. Ripple factor is expressed as:

$$r = \frac{V_{r(rms)}}{V_{dc}}$$

where,

r is the ripple factor,
$V_{r(rms)}$ is the rms value of the ac component,
V_{dc} is the average value of the rectified dc voltage.

Another index used to express the amount of ac ripple is the percent of ripple of a rectified dc voltage. Ripple percentage is expressed as:

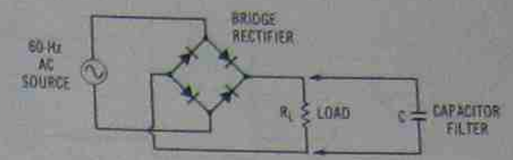
$$\%\ \text{ripple} = \frac{V_{r(rms)}}{V_{dc}} \times 100.$$

A full-wave rectified voltage has less percentage of ripple than a half-wave rectified voltage. When a dc supply must have a low amount of ripple, a full-wave rectifier circuit should be used.

Capacitor Filter

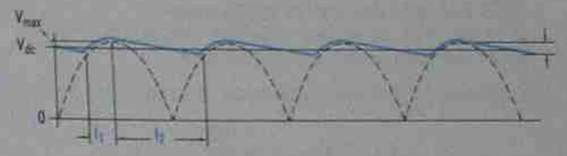
A simple capacitor filter may be used to smooth the ac ripple of a rectifier output. Fig. 5-36 shows the result of adding a capacitor across the output of a single-phase full-wave bridge rectifier. The output waveform after the capacitor has been added is shown in Fig. 5-36C.

The ideal filtered dc voltage would be one with no ac ripple and a value equal to the peak voltage (V_{max}) from the rectifier output. Note that in Fig. 5-36C, the value of V_{dc} is approaching that of V_{max} and compare this to the full-wave rectified voltage of Fig. 5-36B. There are two time intervals shown in Fig. 5-36C. Time period t_1 represents diode conduction which charges the filter capacitor (C) to the peak rectified voltage (V_{max}). The time period t_2 is the time required for the capacitor to discharge through the load (R_L).

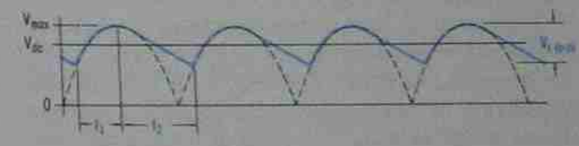


(A) Bridge rectifier circuit with filter capacitor.

(B) Full-wave output waveform with no filter capacitor.



(C) Full-wave output waveform with filter capacitor across load.



(D) Full-wave output waveform with filter capacitor across heavier (lower resistance) load.

Fig. 5-36. Filter capacitor operation.

If a different value of filter capacitor was put into the circuit, a change in the rate of discharge would result. If capacitor C discharged a very small amount, the value of V_{dc} would be closer to the value of V_{max}. With light loads (high resistance), the capacitor filter will supply a high dc voltage with little ripple. However, with a heavy (low resistance) load connected, the dc voltage would drop due to a greater ripple. The increased ripple is caused by the lower resistance discharge path for the filter capacitor. The effect of an increased load on the filter capacitor is shown in Fig. 5-36D.

By utilizing the value indicated on the waveforms of Fig. 5-36, it is possible to express V_{dc} and $V_{r(rms)}$ as:

$$V_{dc} = V_{max} - \frac{V_{r(p\text{-}p)}}{2},$$

and

$$V_{r(rms)} = \frac{V_{r(p\text{-}p)}}{2\sqrt{3}}.$$

We can also express the amount of ripple of a 60-Hz full-wave filter-capacitor circuit with a light load as:

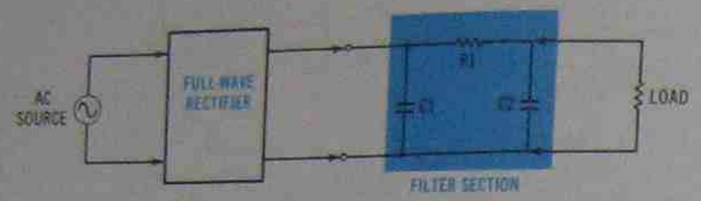


Fig. 5-37. An RC filter circuit.

$$V_{r(rms)} = \frac{2.4I_{dc}}{C},$$

or

$$r = \frac{2.4}{R_L C},$$

where,
I_{dc} is the load current in milliamperes,
C is the filter capacitor value in microfarads,
R_L is the load resistance in kilohms.

The average dc voltage output can be expressed as:

$$V_{dc} = V_{max} - \frac{4.16I_{dc}}{C}.$$

Again, the value of V_{dc} is for a full-wave filter-capacitor circuit with a light load.

With a heavier load (lower resistance) connected to the filter circuit, more current (I_{dc}) is drawn. As I_{dc} increases, V_{dc} decreases. However, if the value of filter capacitor C is made larger, the value of V_{dc} becomes closer to that of V_{max}. The value of C for a full-wave rectifier can be determined by using the equation:

$$C = \frac{2.4I_{dc}}{V_{r(rms)}}.$$

It should be pointed out that as the value of C increases, the value of the peak current through the diodes will also increase. There is, therefore, a practical limit for determining the value of C that is reflected in the foregoing equation.

The capacitor filter produces a high dc voltage with low ac ripple for light loads. However, its major disadvantages are higher ripple and lower V_{dc} at heavier loads, poor voltage regulation, and high peak current through the diodes.

RC Filter

It is possible to improve upon the previous filter circuit by using an RC filter. Fig. 5-37 shows an RC filter stage. This filter has lower ripple than a capacitor filter, but has a lower average dc voltage due to the voltage dropped across R1. The purpose of R1 and C2 is to add another filter network, in addition to C1, to further reduce the ripple. This circuit also operates best with light loads connected. It is possible to have many stages of RC filters to further reduce ac ripple.

Pi or π-Type Filter

The use of the resistor (R1) in the RC filter is not desirable, in many cases, since it reduces the average dc output of the circuit. To compensate for the dc voltage reduction, a Pi or π-type filter may be used. Fig. 5-38 shows this type of filter. The advantage of the choke coil (L1) over the resistor (R1) of the RC filter is that it offers only a small dc series resistance but its ac impedance is much larger. It, therefore, passes dc and blocks the ac component of the rectified voltage. Several sections of this type of filter may also be used to further reduce ac ripple.

DIRECT-CURRENT REGULATION METHODS

The concept of voltage regulation can best be understood by referring to the formula:

$$VR = \frac{V_{NL} - V_{FL}}{V_{FL}} \times 100$$

where,
VR is the voltage regulation in percent,
V_{NL} is the no-load (open-circuit) voltage,
V_{FL} is the rated full-load voltage.

In an ideally regulated circuit, V_{NL} would equal V_{FL}. In all types of power supplies which convert ac to dc the dc output levels are affected by variations in the load. The lower the percentage of regulation (approaching 0%), the better regulated the circuit is. For instance, power supplies are capable of having a voltage regulation of less than 0.01%, which means that the

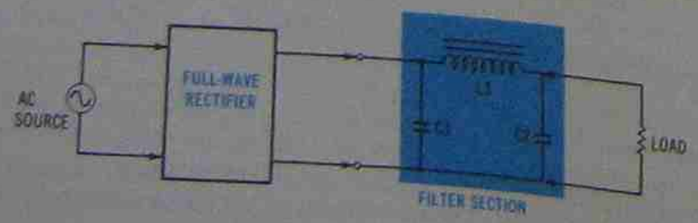
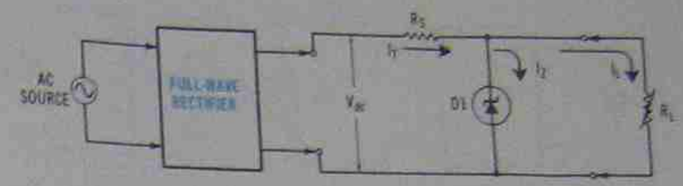


Fig. 5-38. A pi-type filter circuit.

(A) Circuit diagram.



(B) Zener diode characteristic curve.

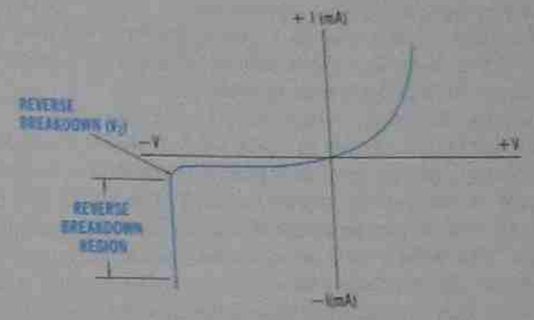


Fig. 5-39. Zener diode voltage regulator.

value of the load has little effect on the dc output voltage produced. A well-regulated dc power supply is necessary for many industrial applications.

Zener Diode Regulators

A simple voltage regulation circuit uses a zener diode as shown in Fig. 5-39. This circuit consists of a series resistor (R_S) and a zener diode (D1) connected to the output of a rectifier circuit. However, we should review zener diode operation before discussing the circuit operation.

Zener diodes are similar to conventional diodes when they are forward biased. When reverse biased, no conduction takes place until a specific value of *reverse breakdown voltage* (or "zener" voltage) is reached. The zener is designed so that it will operate in the reverse breakdown region of its characteristic curve (see Fig. 5-39B). The reverse breakdown voltage is predetermined by the manufacturer. When used as a voltage regulator, the zener diode is reverse biased so that it will operate in the breakdown region. In this region, changes in current through the diode have little effect on the voltage across it. The constant-voltage characteristic of a zener diode makes it desirable for use as a regulating device.

The circuit of Fig. 5-39A is a zener diode shunt regulator. The zener establishes a constant voltage across the load resistance within a range of rectified dc voltages and output load currents. Over this range, the voltage drop across the zener remains constant. The current through the zener (I_z) will vary to compensate for changes in load resistance, since $I_z = I_T - I_L$. Thus, the output voltage will remain constant.

Transistor Voltage Regulators

An improvement over the zener voltage regulator is a transistorized regulator such as shown in the circuit of Fig. 5-40. This regulator has transistor Q1 placed in series with the load device (R_L). Transistor Q1, then, acts as a variable resistance to compensate for changes in the input voltage. The collector-emitter resistance of Q1 varies automatically with changes in the circuit conditions. The zener diode establishes the dc bias placed on the base of transistor Q1. When this circuit is operating properly, if the voltage across the load increases, the rise in emitter voltage makes the base less positive. The current through Q1 will then be reduced, which results in an increase in the collector-emitter resistance of Q1. The increase in resistance will cause a larger voltage drop across transistor Q1, which will now compensate for the change in voltage across the load. Opposite conditions would occur if the load

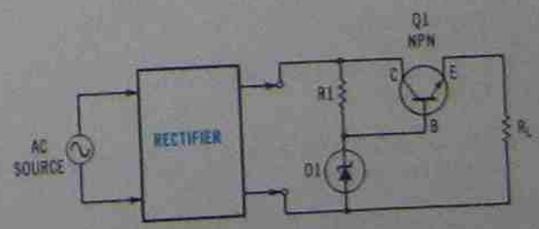


Fig. 5-40. Transistor series voltage regulator circuit.

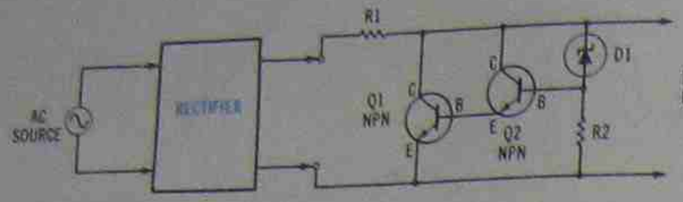
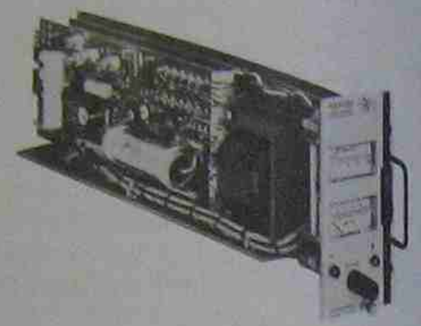


Fig. 5-41. Transistor shunt voltage regulator circuit.

voltage were to decrease. Many variations of this circuit are used in regulated power supplies today.

Shunt regulators are also used in dc power supplies. The circuit of Fig. 5-41 is a shunt voltage regulator. Again, the zener diode (D1) is used to establish a constant dc bias level. Therefore, voltage variations across the dc output will be sensed only by resistor R2. If the dc output voltage rises, an increased positive voltage will be present at the base of transistor Q2. The increased forward bias on transistor Q2 will cause it to conduct more. This makes the base of transistor Q1 more positive and Q1 will then conduct more heavily. Increased current flow through both transistors causes an increase in the voltage drop across resistor R1. This increased voltage drop across R1 will counterbalance the rise in output voltage. Thus, the dc output voltage will remain stabilized. Decreases in dc output voltage would cause the circuit action to reverse. Shunt transistor voltage regulator circuits of many types are also used extensively in power supplies. A regulated power supply is shown in Fig. 5-42.



Courtesy Kepco, Inc.

Fig. 5-42. A regulated dc power supply.

PROBLEMS

1. A 30-volt battery has an output voltage of 29.85 volts when a 10-ohm load is placed across it. What is its internal resistance?

2. A secondary cell has a specific gravity of 1.135. What is its state of charge?

3. A battery is capable of delivering 80 amperes of current for 1.5 hours. What is its ampere-hour rating?

4. A series-wound dc generator has an armature resistance of 1.5 ohms and a field resistance of 4.5 ohms. The voltage across a 12-ohm load is 100 volts. What is the value of (a) armature current and (b) power output?

5. A shunt-wound dc generator has an armature resistance of 2.5 ohms and a field resistance of 40 ohms. Its terminal voltage is 120 volts. Calculate:
   a. Armature current
   b. Field current
   c. Current delivered to the load
   d. Power output

6. A 120-volt dc generator is rated at 20 kW. What is its maximum load current?

7. Calculate the dc output voltages of the following types of rectification systems:
   a. Single-phase half-wave rectifier with 120 volts (rms) applied.
   b. Single-phase full-wave rectifier with 208 volts (rms) applied.
   c. Single-phase bridge rectifier with 50 volts (peak) applied.
   d. Single-phase bridge rectifier with 240 volts (rms) applied.

8. Calculate the ripple factor and the ripple percentage of a filtered rectifier circuit whose dc voltage is 50 volts and whose ac ripple voltage is 2.5 volts (rms).

9. If an additional filter capacitor is added to the circuit of Problem 8 and the ac ripple voltage is reduced to 1.5 volts (rms), what is the new value of the ripple factor and the ripple percentage?

10. Some rectification systems, having capacitor filters, have the following values. What are their dc output voltages?
    a. $V_{max} = 218$ volts, $V_r = 2.5$ volts (p-p).
    b. $V_{max} = 168$ volts, $I_{dc} = 200$ mA, $C = 80$ μF.

11. What are the ripple voltages of full-wave rectifiers with the following values of C and I_{dc}?
    a. 30 μF, 250 mA
    b. 100 μF, 2 amperes
    c. 200 μF, 12 amperes
    d. 10 μF, 130 mA

UNIT II

Power Distribution

After electrical power has been produced, it must be distributed to the location where it will be used. Unit II deals with electrical power distribution systems. The fundamentals of distribution systems are discussed in Chapter 6. This discussion covers an overview of distribution systems, transformer operation, and conductor and insulator characteristics. Chapter 7 examines specialized power distribution equipment such as protective devices, high-voltage equipment, and switch gear. Then, in Chapter 8, single-phase and three-phase distribution systems are discussed. Ground-fault interrupters are also discussed extensively in this chapter, since their use is becoming so widespread in electrical power distribution systems.

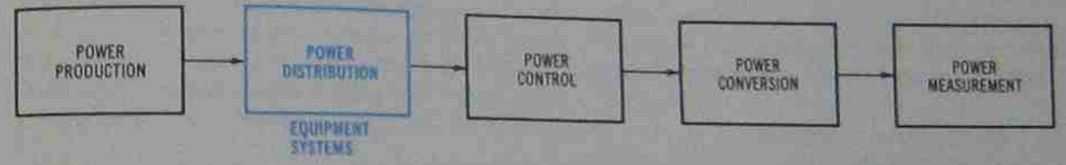


Fig. 2. The electrical power system.

CHAPTER 6

Power Distribution Fundamentals

Power distribution systems are a very important part of electrical power systems. In order to transfer electrical power from an alternating-current or a direct-current source to the place where it will be used, some type of distribution network must be utilized. However, the method used to distribute power from where it is produced to where it is used can be quite simple. For example, a battery could be connected directly to a motor, with only a set of wires to connect them together.

More complex power distribution systems are used, however, to transfer electrical power from the power plant to industries, homes, and commercial buildings. Distribution systems usually employ such equipment as transformers, circuit breakers, and protective devices.

OVERVIEW OF ELECTRICAL POWER DISTRIBUTION

The distribution of electrical power in the United States is normally in the form of three-phase 60-Hz alternating current. This power, of course, can be manipulated or changed in many ways by the use of electrical circuitry. For instance, a rectification system is capable of converting the 60-Hz alternating current into a form of direct current, as was discussed in Chapter 5. Also, single-phase power is generally suitable for lighting and small appliances, such as those used in the home or residential environment. However, where a large amount of electrical power is required, three-phase power is more economical.

The distribution of electrical power involves a very complex system of interconnected power transmission lines. These transmission lines originate at the electrical power-generating stations located throughout the United States. The ultimate purpose of these power transmission and distribution systems is to supply the electrical power necessary for industrial, residential, and commercial use. From the point of view of the systems, we may say that the overall electrical power system delivers power from the source to the load which is connected to it. A typical electrical power distribution system is shown in Fig. 6-1.

Industries use almost 50% of all the electrical power produced, so three-phase power is distributed directly to most industries. Electrical substations, such as the one shown in Fig. 6-2, use massive transformers and associated equipment, such as oil-filled circuit breakers, high-voltage conductors, and huge strings of insulators, in distributing power to industry. From these substations, power is distributed to the industrial sites to energize the industrial machinery, to residential homes, and to commercial users of electrical power.

POWER TRANSMISSION AND DISTRIBUTION

Power transmission and distribution systems are used to interconnect electrical power production systems and to provide a means of delivering electrical power from the generating station to its point of utilization. Most electrical power systems east of the Rocky Mountains are interconnected with one another in a parallel circuit arrangement. These interconnections of power production systems are monitored and controlled, in most cases, by a computerized control center. Such control centers provide a means of data collection and recording, system monitoring, frequency control, and signaling. Computers have become an important means of assuring the efficient operation of electrical power systems.

The transmission of electrical power requires many long interconnected power lines to carry the electrical current from where it is produced to where it is used (see Fig. 6-3). However, overhead power transmission lines require much planning to assure the best use of our land. The location of overhead transmission lines is limited by zoning laws and by populated areas, highways, railroads, and waterways, as well as other topographical and environmental factors. Today, an in-

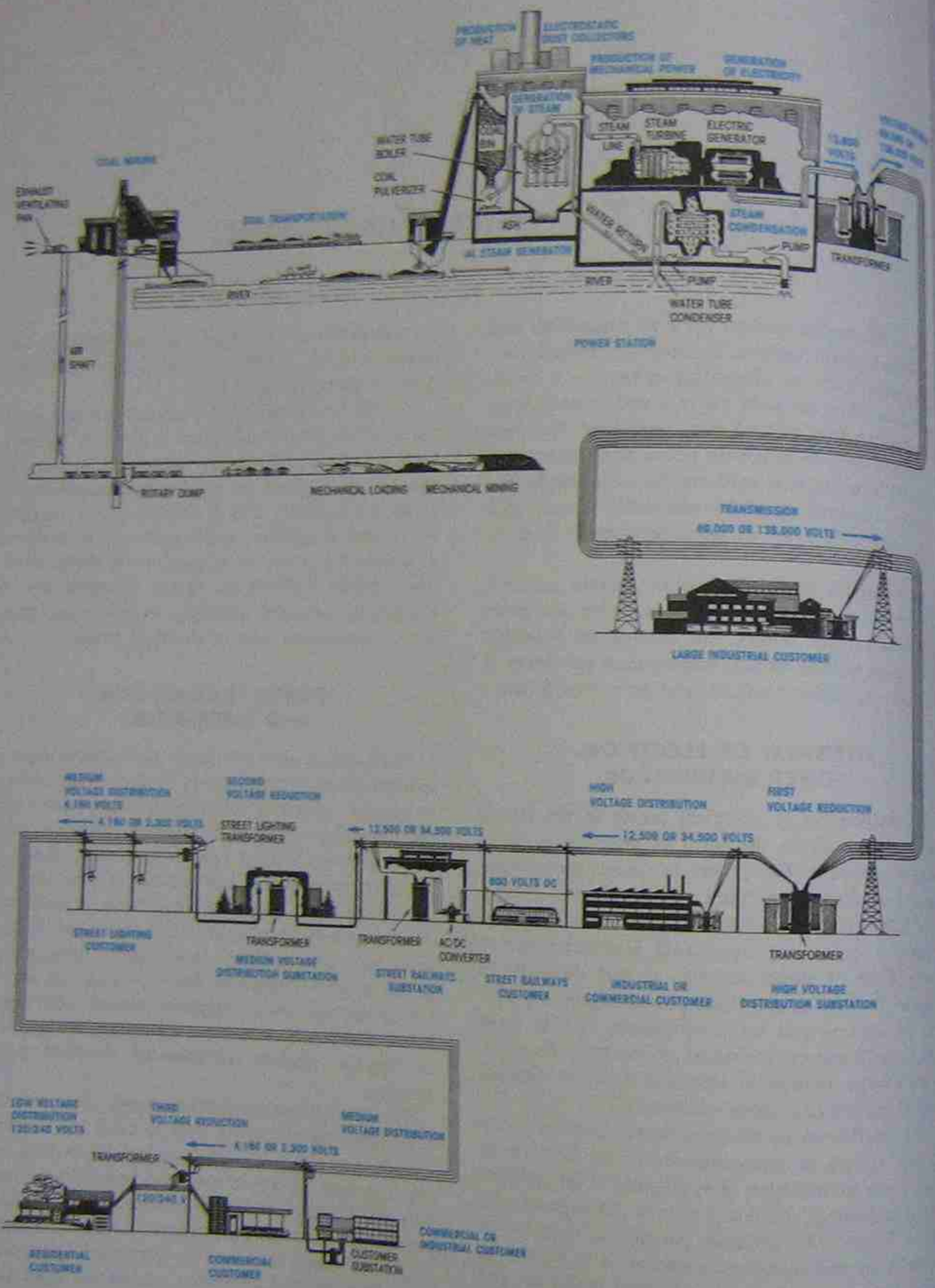


Fig. 6-1. A typical electrical power distribution system.

Courtesy Kentucky Utilities Co

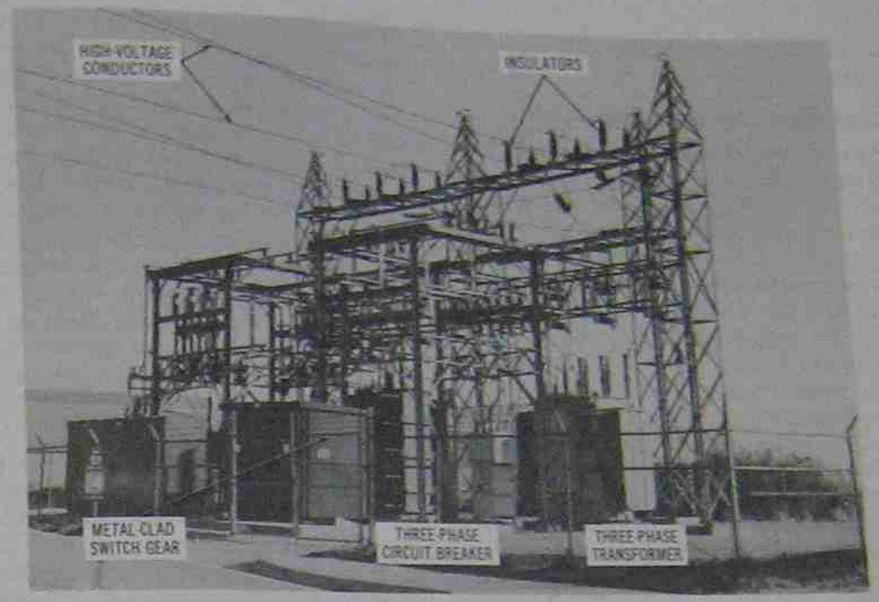


Fig. 6-2. An electrical substation.

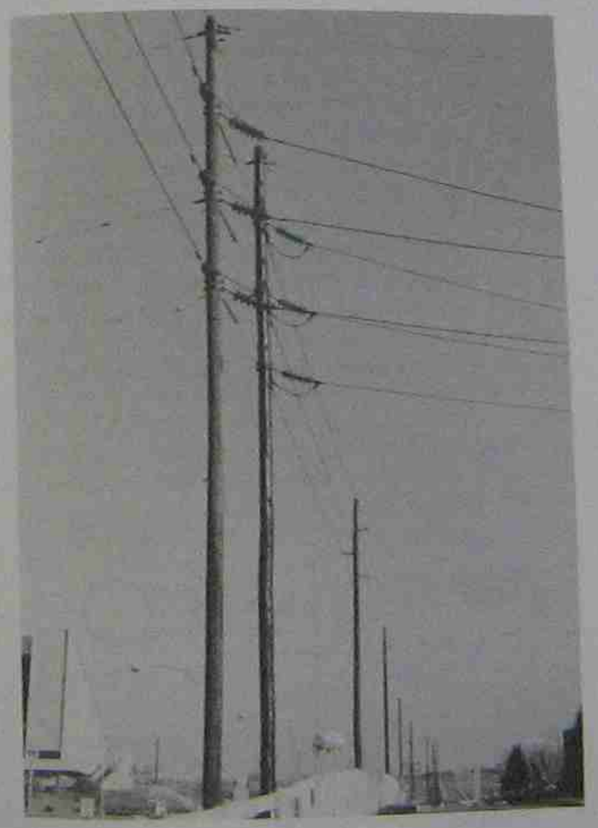


Fig. 6-3. Transmission line of an electrical power system.

creased importance is being placed upon environmental and aesthetic factors. Power transmission lines ordinarily operate at voltage levels from 12 kilovolts to 500 kilovolts of alternating current. Common transmission-line voltages are in the range of 50 to 150 kilovolts of alternating current. High-voltage direct-current overhead transmission lines may become economical although they are not being used to any extent at the present time.

Another option is ultrahigh-voltage transmission lines which use higher ac transmission voltages. Also, underground transmission methods for urban and suburban areas must be considered since right-of-way for overhead transmission lines is limited. Alternating-current overhead transmission voltages have increased to levels as high as 765 kV, with research now dealing with voltages of over 1000 kV. One advantage of overhead cables is their ability to dissipate heat. The use of cryogenic cable may bring about a solution to heat dissipation problems in conductors.

Underground Distribution

The use of underground cable is ordinarily confined to the short lengths required in congested urban areas. The cost of underground cable is much more than for aerial cable. To improve underground cable power-handling capability, research is being done in forced-cooling techniques, such as circulating-oil and with compressed-gas insulation. Another possible method is the use of cryogenic cables or superconductors which

operate at extremely low temperatures and have a large power-handling capability.

High-Voltage Direct-Current Transmission

An alternative to transmitting ac voltages for long distances is high-voltage direct-current (HVDC) power transmission. The HVDC is suitable for long-distance overhead power lines or for underground power lines. Direct-current power lines are capable of delivering more power per conductor than an equivalent ac power line. Due to its fewer power losses, HVDC is even more desirable for underground distribution.

The primary disadvantage of HVDC is the cost of the necessary ac-to-dc conversion equipment. There are, however, some HVDC systems in operation in the United States. At present, HVDC systems have been designed for transmitting voltages of up to 600 kV. The key to the future development of HVDC systems may be the production of solid-state power conversion systems with higher voltage and current ratings. With a continued developmental effort, HVDC should eventually play a more significant role in future electrical power-transmission systems.

Cryogenic Cable

There are some problems involved in installing an overhead electrical power distribution system, particularly in urban areas. One of these problems is obtaining a right-of-way through heavily populated areas for the overhead cable. The difficulty is caused primarily by the unattractive appearance of the lines and the potential danger of the high voltage. The problems associated with overhead transmission lines have led to the development of cryogenic cable for underground power distribution.

Cryogenic cables are not considered to be superconductive, but they do have greater electrical conductivity

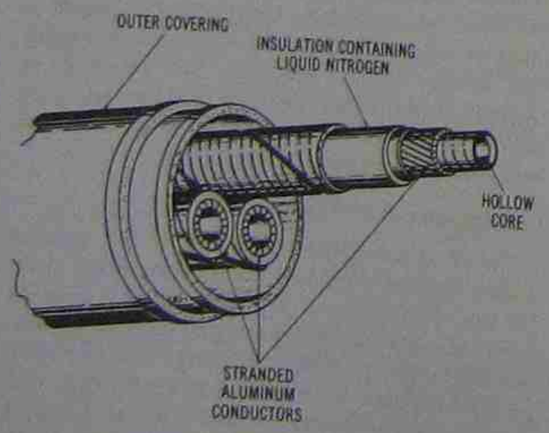


Fig. 6-4. Construction of a cryogenic cable.

at very low temperatures. These cables, which are still in the developmental stage, will use a metallic conductor cooled to the temperature of liquid nitrogen. One advantage of cryogenic cable over conventional cable is that it will have a lower line loss ($I \times R$ loss) due to its greater conductive characteristics.

The design of a cryogenic cable is shown in Fig. 6-4. This design involves the use of three separate cables each having a hollow center for cooling purposes. The conductive portion of the cables is stranded aluminum. The aluminum conductors are wrapped with an insulating material which contains liquid nitrogen. Cryogenic cable has considerable potential in any future development of electrical power systems.

Parallel Operation of Power Systems

Electrical power distribution systems are operated in a parallel circuit arrangement. By adding more power sources (generators) in parallel, a greater load demand or current requirement can be met. On a smaller scale this is like connecting two or more batteries in parallel to provide greater current capacity. Two parallel-connected three-phase alternators are decpicted in Fig. 6-5. Most power plants usually have more than one alternator connected to any single set of power lines inside the plant. These power lines or "bus" lines are usually large copper bar conductors which can carry very high amounts of current. At low-load demand times, only one alternator would be connected to the bus lines.

Fig. 6-6 expands the concept of parallel-connected systems. An illustration of two power plants joined together through a distribution substation is shown. The two power plants might be located 100 miles apart, yet they are connected in parallel to supply power to a specified region. If, for some reason (such as repairs on one alternator), the output of one power plant is reduced, the other power plant is still available to sup-

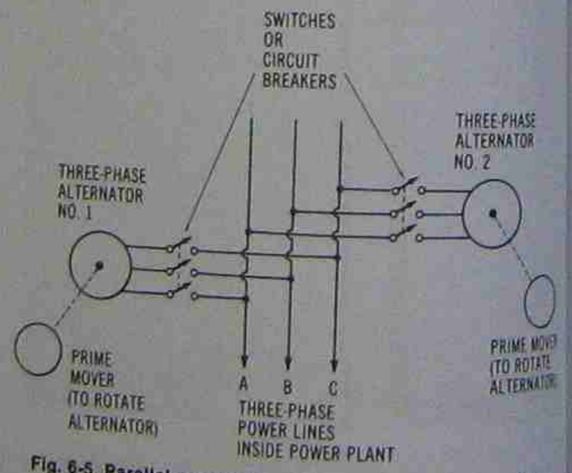


Fig. 6-5. Parallel connection of two three-phase alternators.

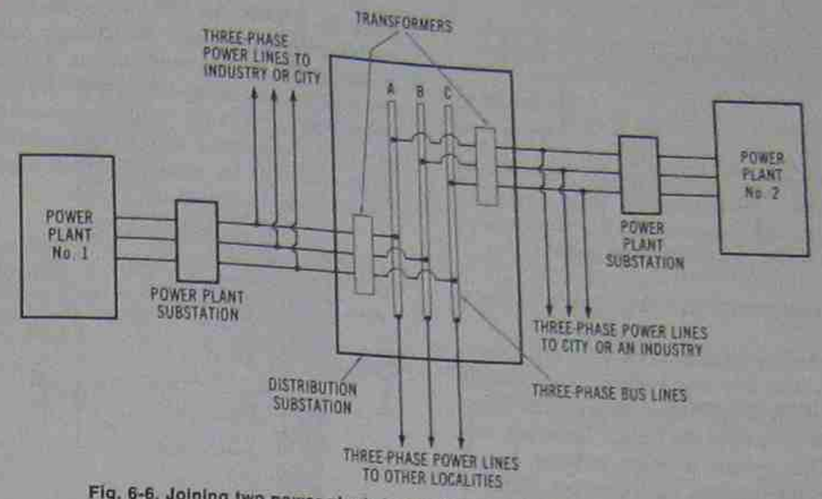


Fig. 6-6. Joining two power plants in parallel as part of a regional power system.

ply power to the requesting localities. It is also possible for power plant No. 1 to supply part of the load requirement ordinarily supplied by power plant No. 2, or vice versa. These regional distribution systems of parallel-connected power sources provide automatic compensation for any increased load demand in any area.

The major problem of parallel-connected distribution systems occurs when excessive load demands are encountered by several power systems in a single region. If all of the power plants in one area are operating near their peak power-output capacity, there is no back-up capability. The equipment-protection system for each power plant and, also, for each alternator in the power plant is designed to disconnect from the system when its maximum power limits are reached. When the power demand on one part of the system becomes too execessive, the protective equipment will disconnect that part of the system. This places an even greater load on the remaining parts of the system. The excessive load now could cause other parts of the system to disconnect. This cycle could continue until the entire system is inoperative. This is what occurs when

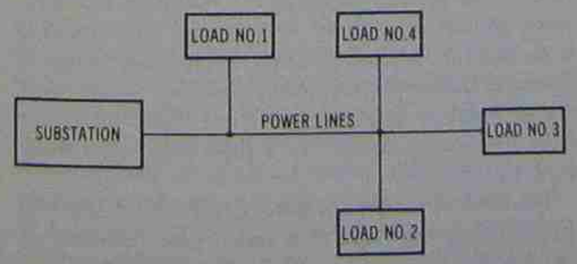


Fig. 6-7. A radial power distribution system.

"blackouts" of power systems take place. No electrical power can be supplied to any part of the system until most of the power plants are put back in operation. The process of putting the output of a power plant back "on-line," when the system is down during power outages, can be a long and difficult procedure.

RADIAL, RING, AND NETWORK DISTRIBUTION SYSTEMS

There are three general classifications of electrical power distribution systems. These are the *radial*, *ring*, and *network* systems shown in Figs. 6-7 through 6-9. Radial systems are the simplest type since the power comes from one power source. A generating system supplies power from the substation through radial lines which are extended to the various areas of a community (Fig. 6-7). Radial systems are the least reliable in terms of continuous service since there is no back-up distribution system connected to the single power source. If any power line opens, one or more loads are interrupted. There is more likelihood of power outages. However, the radial system is the least expensive. This system is used in remote areas where other distribution systems are not economically feasible.

Ring distribution systems (Fig. 6-8) are used in heavily populated areas. The distribution lines encircle the service area. Power is delivered from one or more power sources into substations near the service area. The power is then distributed from the substations through the radial power lines. When a power line is opened, no interruption to other loads occurs. The ring system provides a more continuous service than the radial system. Due to additional power lines and a

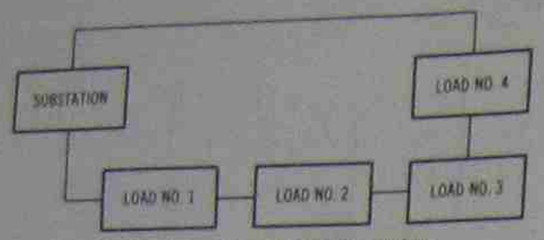


Fig. 6-8. A ring power distribution system.

greater circuit complexity, the ring system is more expensive.

Network distribution systems (Fig. 6-9) are a combination of the radial and ring systems. They usually result when one of the other systems is expanded. Most of the distribution systems in the United States are network systems. This system is more complex but it provides very reliable service to consumers. With a network system, each load is fed by two or more circuits.

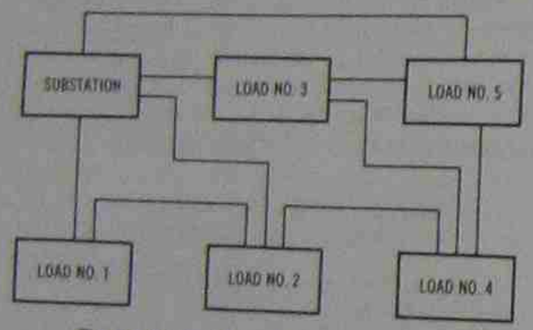
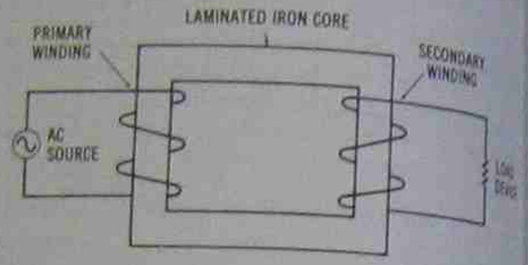


Fig. 6-9. A network power distribution system.

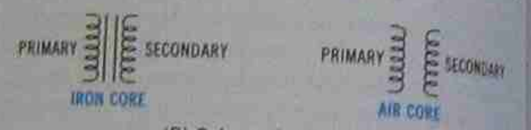
USE OF TRANSFORMERS FOR POWER DISTRIBUTION

The heart of a power distribution system is an electrical device known as a transformer. This device is capable of controlling massive amounts of power for efficient distribution. Transformers are also used for many other applications. A knowledge of transformer operation is essential for understanding power distribution systems. The distribution of alternating-current power is dependent upon the use of transformers at many points along the line of the power distribution system.

It is economically feasible to transmit electrical power over long distances at high voltages since less current is required at high voltages and, therefore, *line loss* (I^2R) is reduced significantly. A typical high-voltage transmission line may extend a distance of 50–100 miles from the generating station to the first substation. These high-voltage power transmission lines may operate at 300,000 to 500,000 volts by using step-up transformers to increase the voltage produced by the ac generators at the power station. Various substations are encountered along the power distribution system where transformers are used to reduce the high transmission voltages to a voltage level such as 480 volts which is suitable for industrial motor loads, or to 120/240 volts for residential use.



(A) Pictorial diagram.



(B) Schematic diagrams.

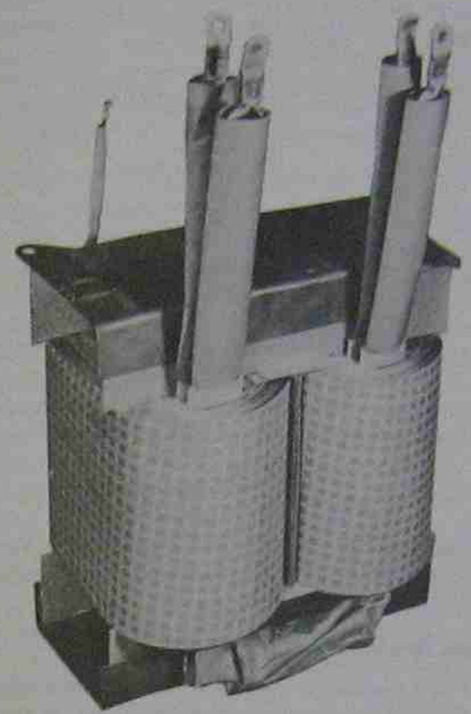
Fig. 6-10. Basic transformer construction.

Transformers provide a means of converting an alternating-current voltage from one value to another. The basic construction of a transformer is illustrated in Fig. 6-10. Notice that the transformer shown consists of two sets of windings which are not physically connected. The only connection between the primary and secondary windings is the magnetic coupling effect known as *mutual induction*, which takes place when the circuit is energized by an alternating-current voltage. The laminated iron core plays an important role in transferring magnetic flux from the primary winding to the secondary winding. A single-phase 25-kVA distribution transformer is shown in Fig. 6-11.

Transformer Operation

If an ac current which is constantly changing in value flows in the primary winding, the *magnetic field* produced around the primary winding will be transferred to the secondary winding. Thus, an *induced voltage* is developed across the secondary winding. In this way, electrical energy can be transferred from the source (primary-winding circuit) to a load (secondary-winding circuit).

The efficient transfer of energy from the primary to the secondary windings of a transformer depends on the coupling of the magnetic field between these two windings. Ideally, all magnetic lines of force developed around the primary winding would be transferred by magnetic coupling to the secondary winding. However, a certain amount of magnetic loss takes place as some lines of force escape to the surrounding air.

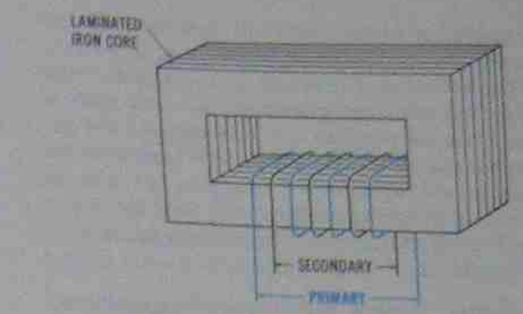


Courtesy General Electric Co.

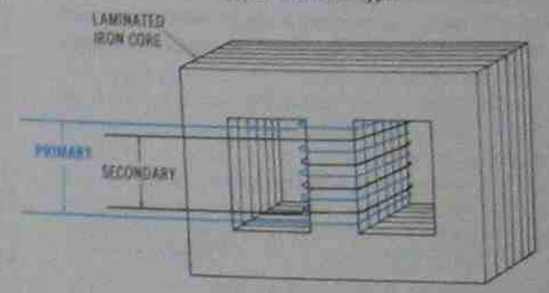
Fig. 6-11. A single-phase 25-kVA distribution transformer.

Transformer Core Construction

In order to decrease the amount of magnetic losses, transformer windings are wound around iron cores. Iron cores concentrate the magnetic lines of force so that better coupling between the primary and secondary windings is accomplished. Two types of transformer cores are illustrated in Fig. 6-12. These cores are made of laminated iron to reduce undesirable eddy currents which are induced into the core material. These eddy currents cause power losses. The diagram of Fig. 6-12A shows a closed-core transformer construction. The transformer windings of the closed-core type are placed along the outside of the metal core. Fig. 6-12B shows the shell-core type of construction. The shell-core construction method produces better magnetic coupling since the transformer windings are surrounded by metal on both sides. Note that the primary and secondary windings of both types are placed adjacent to one another for better magnetic coupling.



(A) Closed-core type.



(B) Shell-core type.

Fig. 6-12. Types of iron-core transformers.

Transformer Efficiency and Losses

Transformers are very efficient electrical devices. A typical efficiency rating for a transformer would be around 98%. Efficiency of electrical equipment is expressed as:

$$\text{Efficiency } (\%) = \frac{P_{out}}{P_{in}} \times 100$$

where,

P_{out} is the power output in watts,
P_{in} is the power input in watts.

The losses that reduce efficiency, in addition to flux leakage, are copper and iron losses. Copper loss is the I^2R loss of the windings, while iron losses are those caused by the metallic core material. The insulated laminations of the iron core help to reduce iron losses.

Step-Up and Step-Down Transformers

Transformers are functionally classified as step-up or step-down types. These types are illustrated in Fig. 6-13. The step-up transformer of Fig. 6-13A has fewer turns of wire on the primary than on the secondary. If the primary winding has 50 turns of wire and the secondary has 500 turns, a turns ratio of 1:10 is developed. Therefore, if 12 volts ac is applied to the primary from the source, 10 times that voltage, or 120 volts ac, will

be transferred to the secondary load (assuming no losses).

The example of Fig. 6-13B is a step-down transformer. The step-down transformer has more turns of wire on the primary than on the secondary. The primary winding of the example has 200 turns while the secondary winding has 100 turns, or a 2:1 ratio. If 120 volts ac is applied to the primary from the source, then one-half that amount, or 60 volts ac, will be transferred to the secondary load.

Transformer Voltage and Current Relationships

From the preceding examples, a direct relationship is shown between the primary and secondary turns and the voltages across each winding. This relationship may be expressed as:

$$\frac{V_p}{V_s} = \frac{N_p}{N_s}$$

where,

V_p is the voltage across the primary winding,
V_s is the voltage across the secondary winding,
N_p is the number of turns in the primary winding,
N_s is the number of turns in the secondary winding.

The transformer is a power-control device; therefore, the following relationship can be expressed:

$$P_p = P_s + \text{losses}$$

where,

P_p is the primary power,
P_s is the secondary power,

and the losses are those that ordinarily occur in a transformer. In transformer theory, an ideal device is usually assumed, and losses are not considered. Thus, since $P_p = P_s$ and $P = V \times I$, then

$$V_s \times I_p = V_s \times I_s$$

where,

I_p is the primary current,
I_s is the secondary current.

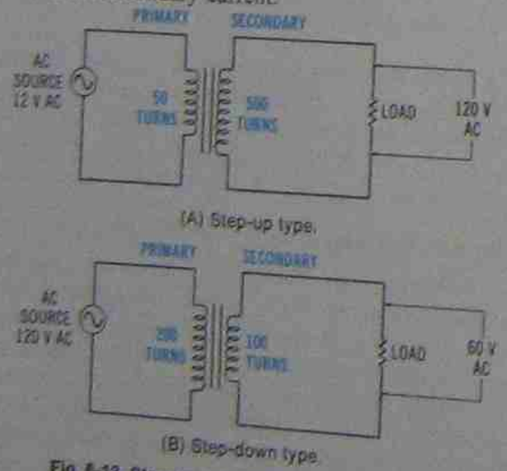


Fig. 6-13. Step-up and step-down transformers.

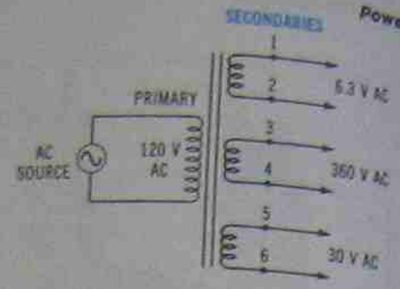


Fig. 6-14. Transformer with multiple secondary windings.

Therefore, if the voltage across the secondary is stepped up to twice the voltage across the primary, then the secondary current will be stepped down to one-half the primary current. The current relationship of a transformer is thus expressed as:

$$\frac{I_p}{I_s} = \frac{N_s}{N_p}.$$

Note that whereas the voltage-turns ratio is a direct relationship, the current-turns ratio is an *inverse* relationship.

Multiple Secondary Transformers

It is also possible to construct a transformer which has multiple secondary windings, as shown in Fig. 6-14. This transformer is connected to a 120-volt ac source which produces the primary magnetic flux. The secondary has two step-down windings and one step-up winding. Between points 1 and 2, a voltage of 6.3-volts ac could be supplied. This voltage is one standard voltage for vacuum-tube filament supplies. Between point 5 and point 6, 30-volts ac may be obtained, and between points 3 and 4, a voltage of 360-volts ac can be supplied to a load, such as the plate of a vacuum tube or a gaseous tube. This type of transformer is often used for the power supply of various types of electronic equipment and instruments.

Autotransformers

Another specialized type of transformer is the autotransformer, shown in Fig. 6-15. The autotransformer has only one winding, with a common connection between the primary and secondary. The principle of

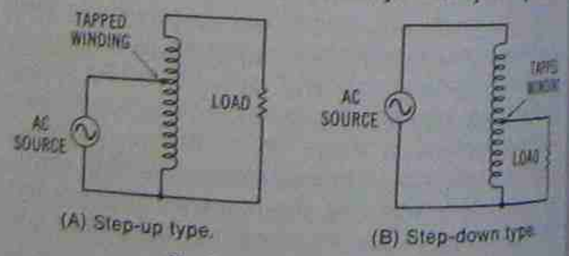


Fig. 6-15. Autotransformers.

operation of the autotransformer is similar to other transformers. Both the step-up and step-down types are shown in Fig. 6-15. The control device shown in Fig. 6-16 is a variable autotransformer in which the winding tap may be adjusted along the entire length of the winding to provide a variable ac voltage to a load.

Transformer Polarity and Ratings

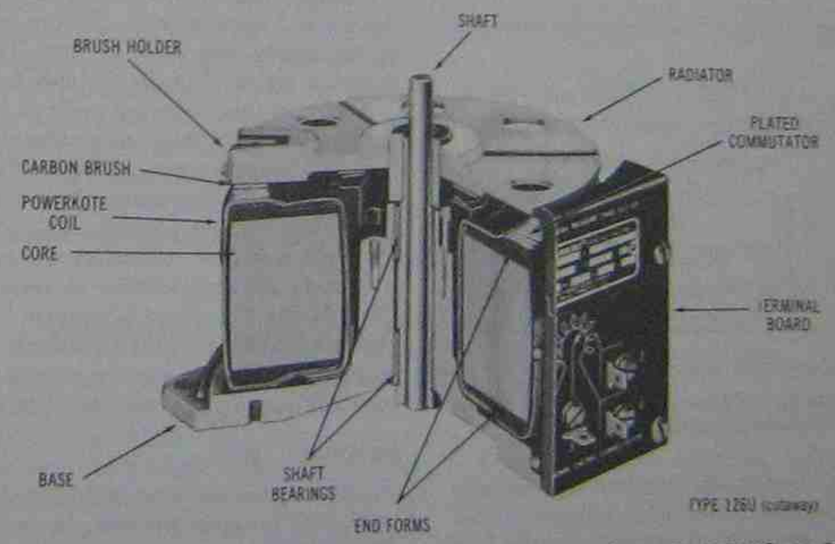
Power distribution transformers usually have polarity markings so that their windings may be connected in parallel to increase their current capacity. The standard markings are H_1, H_2, H_3, etc., for the high-voltage windings, and X_1, X_2, X_3, etc., for the low-voltage windings. Many power transformers have two similar primary windings and two similar secondary windings to make them adaptable to different voltage requirements simply by changing from a series to a parallel connection. The voltage combinations available from this type of transformer are shown in Fig. 6-17.

The ratings of power transformers are very important. Usually transformers are rated in kilovoltamperes (kVA). A kilowatt rating is not used since it would be misleading due to the various power-factor ratings of industrial loads. Other power-transformer ratings usually include frequency, rated voltage of each winding, and an impedance rating.

Power transformers located along a power distribution system operate at very high temperatures. The three-phase transformer shown in Fig. 6-18 shows the cooling equipment which is necessary for large transformers. The purpose of the cooling equipment is to conduct heat away from the transformer windings. Several power transformers are of the liquid-immersed type. The windings and core of the transformer are immersed in an insulating liquid which is contained in the transformer enclosure. The liquid insulates the windings as well as conducting heat away from them. One insulating liquid that is used extensively is called *Askarel*. Some transformers, called dry types, use forced air or inert gas as coolants. Some locations, particularly indoors, are considered hazardous for the use of liquid-immersed transformers. However, most transformers rated at over 500 kVA are liquid filled.

Transformer Malfunctions

Transformer malfunctions result when a circuit problem causes the insulation to break down. Insulation breakdown permits electrical arcs to flow from one winding to an adjacent winding. These arcs, which may be developed throughout the transformer, cause a decomposition of the paper or oil insulation used in the transformer. This can be a particularly hazardous problem for larger power transformers, since a gas may be produced due to the reaction of the electric arc and the insulating material. For this reason, it is very important for circuit protection to be provided for transformers. They should have power removed promptly whenever some type of fault develops. Current-limiting fuses may also be used to respond rapidly to any circuit malfunction.

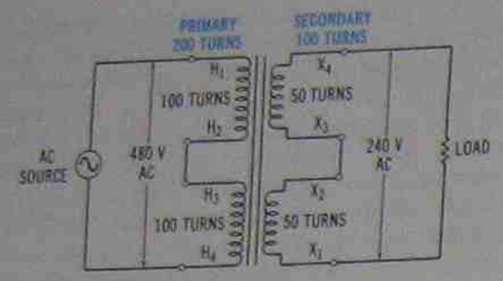


Courtesy The Superior Electric Co.

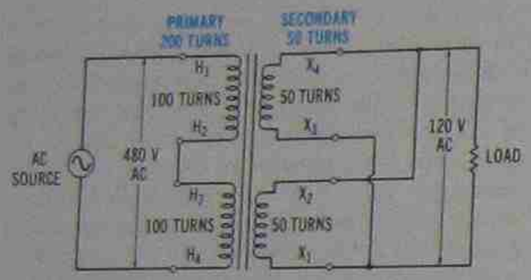
Fig. 6-16. Cutaway view of a variable autotransformer.

CONDUCTORS IN POWER DISTRIBUTION SYSTEMS

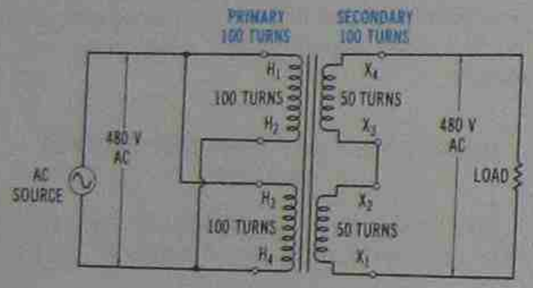
The portions of the electrical distribution system which carry current are known as conductors. Conduc-



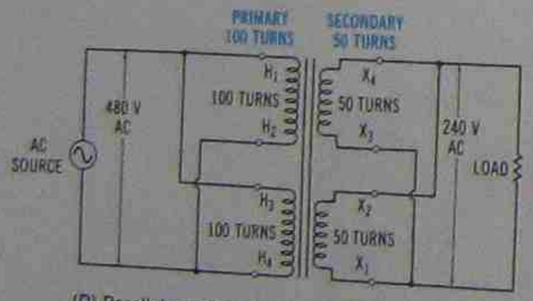
(A) Series-connected primary and secondary.



(B) Series-connected primary; parallel-connected secondary.



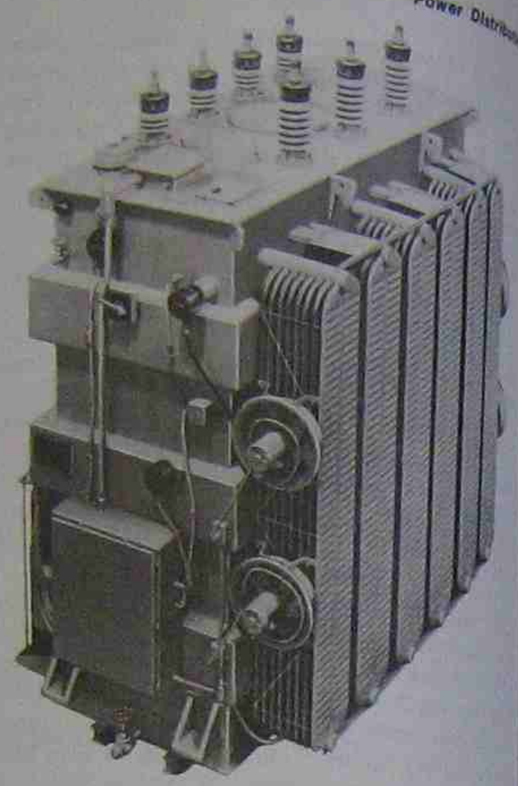
(C) Parallel-connected primary; series-connected secondary.



(D) Parallel-connected primary and secondary.

Fig. 6-17. Some transformer connection methods for various voltage combinations.

tors may be in the form of solid or stranded wires, cable assemblies, or large metallic bus-bar systems. A conductor may have insulation or, in some cases, be bare metal.



Courtesy Kuhlman Electric Co.

Fig. 6-18. A large three-phase power transformer.

Conductor Characteristics

Round conductors are measured by using an American Wire Gage (AWG). The sizes range from No. 36 (smallest) to No. 0000 (largest), with 40 sizes within this range. The cross-sectional area of a conductor doubles with each increase of three sizes and the diameter doubles with every six sizes. The area of conductors is measured in circular mils (cmil).

Almost all conductors are made of either copper or aluminum. Both of these metals possess the necessary flexibility, current-carrying ability, and economical cost to act as efficient conductors. Copper is a better conductor; however, aluminum is 30% lighter in weight. Therefore, aluminum conductors are used when weight is a factor for consideration in conductor selection. One specialized overhead power-line conductor is the aluminum-conductor steel-reinforced (ACSR) type used for long-distance power transmission. This type of conductor has stranded aluminum wires.

Conductor Types

Copper is still the most widely used conductor material, both for solid and for stranded electrical wire. The availability of a variety of thermosetting and thermoplastic insulating materials offers great flexibility in

Table 6-1. Operating Temperature Ranges of Various Types of Insulation

Type of Insulation	Temperature Range (°C)
Neoprene	−30° to 90°
Teflon	−70° to 200°
Polyethylene	−60° to 80°
Rubber	−40° to 75°
Vinyl	−20° to 80°
Polypropylene	−20° to 105°

meeting the requirements for most conductor applications. The operating temperature ranges for various types of insulation are given in Table 6-1.

Copper has a combination of various properties, such as malleability, good strength, and high electrical and thermal conductivity. It also has the capability of being alloyed or coated with other metals. Copper may be plated with silver to produce a better solderability and, also, a conductor that has better high-frequency characteristics. This is due to the high conductivity of the silver and the "skin effect" present at higher frequencies.

Where little vibration and no flexing are required of a wire or cable, single-strand conductors may be used. The advantage of a single-strand conductor is its lower cost compared to that of equivalent types of stranded wire. Wire and cable with solid conductors may be used as interconnection wires for electrical instruments and similar equipment. Stranded conductors are used to provide more flexibility. They, also, have a longer usage life than do solid conductors. If a solid conductor were cut during its installation by wire strippers, it would probably break after being bent a few times. However, stranded wire would not break in this situation. Wires having from 26 to 41 strands may be used where much flexibility is needed while wires with from 65 to 105 strands may be used for special purposes.

Flat or round braided conductors are occasionally used for certain applications where they are usually better suited than are solid or stranded cables. These conductors are seldom insulated since this would hinder their flexibility.

CONDUCTORS

The unit of measurement for conductors is the *circular mil* (cmil) since most conductors are round. One mil is equal to 0.001 inch (0.0254 mm); thus, one circular mil is equal to a circle whose diameter is 0.001 inch. The cross-sectional area of a conductor (in circular mils) is equal to its diameter D (in mils) squared, or cmil = D^2. For example, if a conductor is a ¼ inch (6.35 mm) in diameter, its circular mil area can be

found as follows. The decimal equivalent of ¼ inch is 0.250 inch which equals 250 mils. Inserting this value into the formula for the cross-sectional area of a conductor gives you:

$$\begin{aligned}\text{Area} &= D^2 \text{ (in mils)}\\ &= (250)^2\\ &= 62{,}500 \text{ cmils}\end{aligned}$$

If the conductor is not round in shape, its area may still be found by applying the following formula:

$$\text{Area (in cmil)} = \frac{\text{Area (in square mils)}}{0.7854}$$

This formula allows us to convert the dimensions of a conductor to square mils and, then, to an equivalent value in circular mils. For example, if a conductor is ½ inch × ¾ inch (12.7 mm × 19.05 mm), the circular mil area may be found using the following method. Again, convert the fractional inches into decimal values and, then, into equivalent mil values. Thus, ½ inch equals 0.5 inch which equals 500 mils, and ¾ inch is 0.75 inch which equals 750 mils. Using the formula for square mils and substituting, you have:

$$\begin{aligned}\text{Area} &= \frac{\text{Area (in square mils)}}{0.7854}\\ &= \frac{500 \text{ mils} \times 750 \text{ mils}}{0.7854}\\ &= \frac{375{,}000 \text{ mils}^2}{0.7854}\\ &= 477{,}463.7 \text{ cmils}\end{aligned}$$

We can also use the circular mil area of a conductor, which may be found in any standard conductor table, to find the diameter of a conductor. If a table shows that the circular mil area of a conductor is equal to 16,510 cmils (a No. 8 AWG conductor), its diameter is found by the following method. Since

$$D^2 = \text{cmil},$$

then,

$$\begin{aligned}D &= \sqrt{\text{cmil}}\\ &= \sqrt{16{,}510 \text{ cmils}}\\ &= 128.5 \text{ mils}\\ &= 0.1285 \text{ inch.}\end{aligned}$$

RESISTANCE OF CONDUCTORS

The *resistance* of a conductor expresses the amount of opposition it will offer to the flow of electrical current. The unit of measurement for resistance is the ohm (Ω). The *resistivity* (ρ) of a conductor is the resistance for a specified cross-sectional area and length.

This measurement is given in circular mil-feet (cmil-ft). The resistivity of a conductor changes with the temperature, so resistivity is usually specified at a temperature of 20° Celsius. The resistivity for some common types of conductors is listed in Table 6-2.

Table 6-2. Resistivity of Common Conductors

Conductor	Resistivity in ohms per cmil-ft
Silver	9.8
Copper	10.4
Aluminum	17.0
Tungsten	33.0
Nickel	50.0
Iron	60.0

We can use Table 6-2 to calculate the resistance of any size conductor. We know that resistance increases as the length increases and decreases as the cross-sectional area increases. The following method can be used to find the resistance of 500 feet (152.4 meters) of aluminum conductor that is ¼ inch (6.35 mm) in diameter. According to Table 6-2, aluminum has a resistivity of 17 ohms. The diameter (D) equals ¼ inch which equals 0.250 inch which is the equivalent of 250 mils. Using the formula and substituting, we have:

$$\text{Resistance} = \frac{\text{Resistivity} \times \text{Length (in feet)}}{\text{Diameter}^2 \text{ (in mils)}}$$

$$= \frac{17 \times 500}{(250)^2}$$

$$= \frac{8{,}500}{62{,}500}$$

$$= 0.136 \text{ ohm}$$

CONDUCTOR SIZES

Table 6-3 lists the sizes of copper and aluminum electrical conductors. The American Wire Gage (AWG) is the standard used to measure the diameter of conductors. The sizes range from No. 40 AWG which is the smallest to No. 0000 AWG. Sizes larger than No. 0000 AWG are expressed in million circular mil (MCM) units.

Note, in Table 6-3, that as the AWG size number becomes smaller, the conductor is larger. Sizes up to No. 8 AWG are solid conductors, while larger wires have from 7 to 61 strands. Table 6-3 also lists the dc resistance (in ohms per 1000 feet) of the copper and aluminum conductors. These values are used to determine conductor voltage drop in power distribution systems.

Table 6-3. Sizes of Copper and Aluminum Conductors

Size (AWG or MCM)	Area (cmil)	Number of Wires	Diameter of Each Wire (in.)	DC Resistance (Ω/1000 ft) 25°C	
				Copper	Aluminum
18	1,620	1	0.0403	6.51	10.7
16	2,580	1	0.0508	4.10	6.72
14	4,110	1	0.0641	2.57	4.22
12	6,530	1	0.0808	1.62	2.66
10	10,380	1	0.1019	1.018	1.67
8	16,510	1	0.1285	0.6404	1.05
6	26,240	7	0.0612	0.410	0.674
4	41,740	7	0.0772	0.259	0.424
3	52,620	7	0.0867	0.205	0.336
2	66,360	7	0.0974	0.162	0.266
1	83,690	19	0.0664	0.129	0.211
0	105,600	19	0.0745	0.102	0.168
00	133,100	19	0.0837	0.0811	0.133
000	167,800	19	0.0940	0.0642	0.105
0000	211,600	19	0.1055	0.0509	0.0836
250	250,000	37	0.0822	0.0431	0.0708
300	300,000	37	0.0900	0.0360	0.0590
350	350,000	37	0.0973	0.0308	0.0505
400	400,000	37	0.1040	0.0270	0.0442
500	500,000	37	0.1162	0.0216	0.0354
600	600,000	61	0.0992	0.0180	0.0295
700	700,000	61	0.1071	0.0154	0.0253
750	750,000	61	0.1109	0.0144	0.0236
800	800,000	61	0.1145	0.0135	0.0221
900	900,000	61	0.1215	0.0120	0.0197
1000	1,000,000	61	0.1280	0.0108	0.0177

AMPACITY OF CONDUCTORS

A measure of the ability of a conductor to carry electrical current is called *ampacity*. All metal materials will conduct electrical current to some extent; however, copper and aluminum are the two most desirable types used. Copper is the most used metal since it is the better conductor of the two and is physically stronger. However, aluminum is usually used where weight is a factor, such as for long-distance overhead power lines. The weight of copper is almost three times that of a similar volume of aluminum; however, the resistance of aluminum is over 150% that of copper. The ampacity of an aluminum conductor is, therefore, less than a similar size copper conductor. In a wiring design, aluminum conductors, that are one size larger than the copper conductors necessary to carry a specific amount of current, are ordinarily used to allow for this difference (see Table 6-3).

The ampacity of conductors depends upon several factors such as the type of material, cross-sectional area, and the type of area in which they are installed. Conductors in the open or in "free air" dissipate heat much more rapidly than they do if they are enclosed in a metal raceway or plastic cable. When several con-

Table 6-4. Allowable Ampacities of Single Conductors in Free Air

Wire Size	Copper		Aluminum	
	With R, T, TW Insulation	With RH, RHW, TH, THW Insulation	With R, T, TW Insulation	With RH, RHW, TH, THW Insulation
14	20	20		
12	25	25	20	20
10	40	40	30	30
8	55	65	45	55
6	80	95	60	75
4	105	125	80	100
3	120	145	95	115
2	140	170	110	135
1	165	195	130	155
0	195	230	150	180
00	225	265	175	210
000	260	310	200	240
0000	300	360	230	280
250	340	405	265	315
300	375	445	290	350
350	420	505	330	395
400	455	545	355	425
500	515	620	405	485
600	575	690	455	545
700	630	755	500	595
750	655	785	515	620
800	680	815	535	645
900	730	870	580	700
1000	780	935	625	750

ductors are contained within the same enclosure, heat dissipation is a greater problem.

AMPACITY TABLES

Tables 6-4 through 6-6 are used for conductor ampacity calculations for electrical wiring design. These tables are simplified versions of those given in the National Electrical Code (NEC). Table 6-4 is used to determine conductor ampacity when a single conductor is mounted in free air. Table 6-5 is used to find the ampacity of conductors when not more than three are mounted in a raceway or cable. These two tables are based on ambient temperatures of 30° Celsius (86° Fahrenheit). Table 6-6 lists the correction factors which are used for temperatures over 30° C.

As an example, we will find the ampacity of three No. 10 copper conductors with RHW insulation which are mounted in a raceway. They will be located in a foundry area where temperatures reach 50° C. The ampacity for No. 10 RHW copper wire is 30 amperes (from Table 6-5). The correction factor for an RHW-insulated conductor at 50° C ambient temperature is 0.75 (Table 6-6). Therefore,

$$30 \text{ amperes} \times 0.75 = 22.5 \text{ amperes.}$$

Table 6-5. Ampacities of Conductors in a Raceway or Cable (3 or less)

Wire Size	Copper		Aluminum	
	With R, T, TW Insulation	With RH, RHW, TH, THW Insulation	With R, T, TW Insulation	With RH, RHW, TH, THW Insulation
14	15	15		
12	20	20	15	15
10	30	30	25	25
8	40	45	30	40
6	55	65	40	50
4	70	85	55	65
3	80	100	65	75
2	95	115	75	90
1	110	130	85	100
0	125	150	100	120
00	145	175	115	135
000	165	200	130	155
0000	195	230	155	180
250	215	255	170	205
300	240	285	190	230
350	260	310	210	250
400	280	335	225	270
500	320	380	260	310
600	355	420	285	340
700	385	460	310	375
750	400	475	320	385
800	410	490	330	395
900	435	520	355	425
1000	455	545	375	445

USE OF INSULATION IN POWER DISTRIBUTION SYSTEMS

Synthetic insulation for wire and cable is classified into two broad categories—thermosetting and thermoplastic. The mixtures of materials within each of these categories are so varied as to make the available number of insulations almost unlimited. Most insulation is composed of compounds made of synthetic rubber polymers (thermosetting) and from synthetic materials (thermoplastics). These synthetic materials are combined to provide specific physical and electrical properties.

Thermosetting materials are characterized by their ability to be stretched, compressed, or deformed within

Table 6-6. Correction Factors for Temperatures Above 30° C

Ambient Temperature		Conductor Correction Factor	
C°	F°	R, T, TW	RH, RHW, TH, THW
40	104	0.82	0.88
45	113	0.71	0.82
50	122	0.58	0.75
55	131	0.41	0.67
60	140	—	0.58
70	158	—	0.35

reasonable limits under mechanical strain and, then, return to their original shape when the stress is removed.

Thermoplastic insulation materials are best known for their excellent electrical characteristics and relatively low cost. These materials are popular since much thinner insulation thicknesses may be used to obtain good electrical properties, particularly at the higher voltages.

There are many types of insulation used today for electrical conductors. Some new materials have been developed that will last for exceptionally long periods of time and will withstand very high operating temperatures. The operating conditions where the conductors are used mainly determine the type of insulation required. For instance, system voltage, heat, and moisture affect the type of insulation required. Insulation must be used which will withstand both the heat of the surrounding atmosphere and that developed by the current flowing through the conductor. Exceptionally large currents will cause excessive heat to be developed in a conductor. Such heat could cause insulation to melt or burn. This is why overcurrent protection is required as a safety factor to prevent fires. The ampacity of current-carrying capacity of a conductor depends upon the type of insulation used. The NEC has developed a system of abbreviations for identifying various types of insulation. Some of the abbreviations are shown in Table 6-7.

Table 6-7. Common Abbreviations for Types of Electrical Insulation

Abbreviation	Type of Insulation
R	Rubber—140° F
RH	Heat-Resistant Rubber—167° F
RHH	Heat-Resistant Rubber—194° F
RHW	Moisture and Heat-Resistant Rubber—167° F
T	Thermoplastic—140° F
THW	Moisture and Heat-Resistant Thermoplastic—167° F
THWN	Moisture and Heat-Resistant Thermoplastic With Nylon—194° F

PROBLEMS

1. A 1500-turn primary winding has 120 volts applied. The secondary voltage is 20 volts. How many turns of wire does the secondary winding have?

2. When a 200-ohm resistance is placed across a 240-volt secondary winding, the primary current is 30 amperes. What is the value of the primary voltage of the transformer?

3. A transformer has a 20:1 turns ratio. The primary voltage is 4800 volts. What is the secondary voltage?

4. A transformer has a 2400-volt primary winding and a 120-volt secondary. The primary winding has 1000 turns. How many turns of wire does the secondary winding have?

5. A 240-volt to 4800-volt transformer has a primary current of 95 amperes and a secondary current of 4 amperes. What is its efficiency?

6. A transformer has a 20-kVA power rating. Its primary voltage is 120 volts and its secondary voltage is 480 volts. What are the values of its maximum primary current and secondary current?

7. Convert the following diameters of electrical conductors into mils:

   a. $\frac{1}{8}$ inch
   b. $\frac{1}{4}$ inch
   c. $\frac{3}{8}$ inch
   d. $\frac{1}{2}$ inch
   e. 0.2 inch
   f. 0.28 inch
   g. 0.15 inch
   h. 0.66 inch

8. Calculate the cross-sectional area of the following electrical conductors (in circular mils):

   a. $\frac{3}{16}$ inch diameter.
   b. 0.5 inch square conductor.
   c. 0.38 inch diameter.
   d. $\frac{1}{2}$ inch $\times$ $\frac{3}{8}$ inch rectangular conductor.

9. Calculate the resistance of 480 feet of copper conductor that is 0.28 inch in diameter.

10. Use the proper *formula* to calculate the resistances of the following electrical conductors:

    a. 380 feet of No. 10 AWG copper.
    b. 2500 feet of No. 000 AWG copper.
    c. 230 feet of 500 MCM copper.
    d. 1900 feet of No. 8 AWG aluminum.
    e. 220 feet of No. 10 AWG aluminum.

11. Use the proper *table* to calculate the resistance of the following electrical conductors:

    a. 600 feet of No. 0000 AWG copper.
    b. 500 feet of No. 1 AWG aluminum.
    c. 300 feet of No. 12 AWG copper.
    d. 200 feet of 250 MCM aluminum.
    e. 1800 feet of No. 10 AWG copper.

12. In order to carry the following currents, what are the minimum sizes of conductors needed? No more than three conductors will be used in the same raceway.

    a. 380 amperes using THW copper.
    b. 95 amperes using THW aluminum.
    c. 180 amperes using RH copper.
    d. 230 amperes using TW copper.
    e. 230 amperes using R copper.
    f. 650 amperes using RHW copper.
    g. 580 amperes using T copper.
    h. 82 amperes using TH aluminum.

13. Find the equivalent size of THW aluminum conductors for the following copper conductors:

    a. 500 MCM, TW.
    b. 750 MCM, TH.
    c. No. 00 AWG, R.
    d. No. 4 AWG, T.
    e. No. 8 AWG, RHW.

CHAPTER 7

Power Distribution Equipment

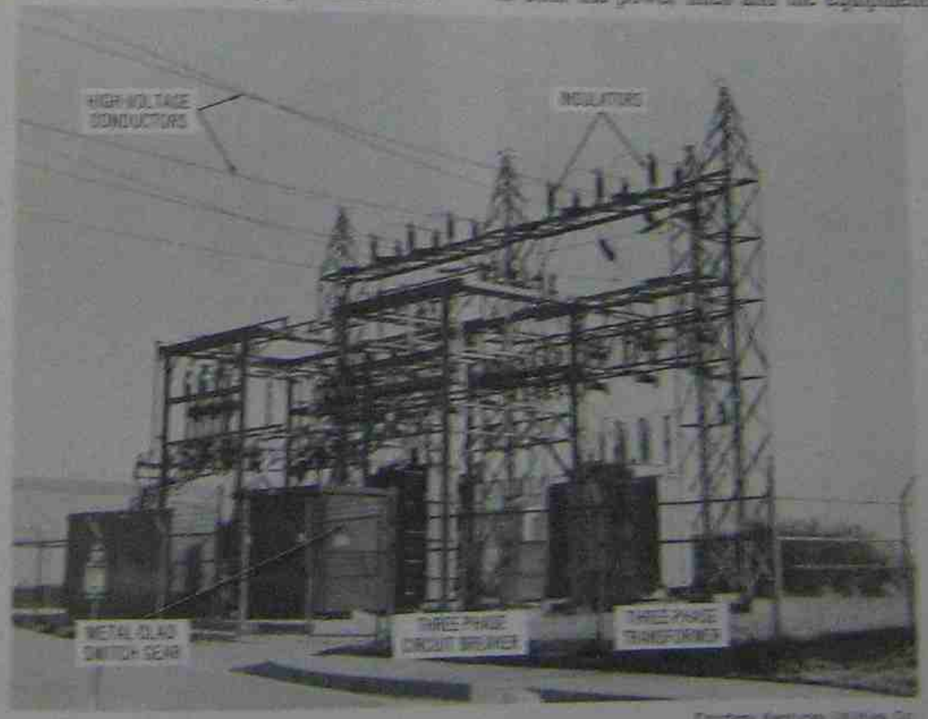
In order to distribute electrical power, it is necessary to use many types of specialized equipment. The electrical power system consists of such specialized equipment as power transformers, high-voltage fuses and circuit breakers, lightning arresters, power-factor-correcting capacitors, and power-metering systems. Some types of specialized power distribution equipment will be discussed in this chapter.

EQUIPMENT USED AT SUBSTATIONS

Substations are very important parts of the electrical power systems. The link between the high-voltage transmission lines and the low-voltage power distribution systems is the substation. The function of a distribution substation, such as the one shown in Fig. 7-1, is to receive electrical power from a high-voltage system and convert it to voltage levels suitable for industrial, commercial, or residential use. The major functional component of a substation is the transformer, whose basic characteristics were discussed previously. However, there are many other types of specialized equipment required for the operation of a substation.

High-Voltage Fuses

Since power lines are frequently short circuited, various protective equipment is used to prevent damage to both the power lines and the equipment. This pro-

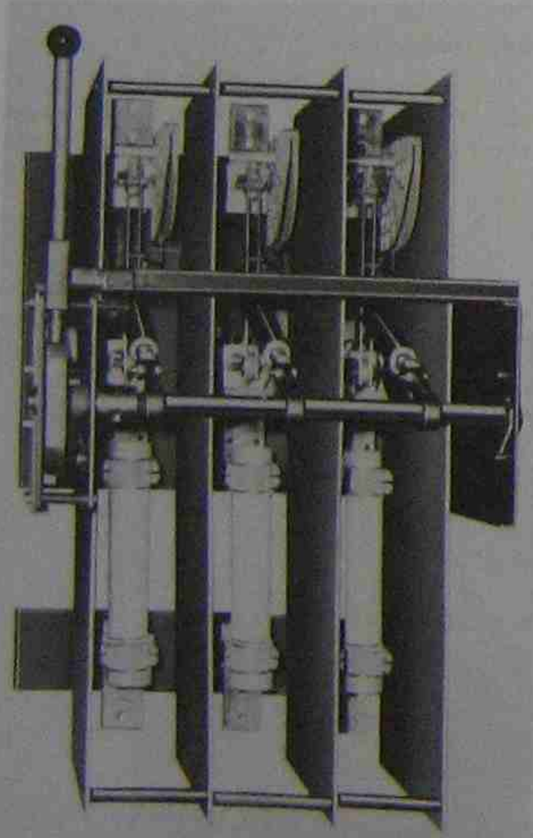


Courtesy Kentucky Utilities Co.

Fig. 7-1. An electrical substation.

tective equipment must be designed to handle high voltages and currents. Either fuses or circuit breakers may be used to protect high-voltage power lines. High-voltage fuses (those used for over 600 volts) are made in several ways. An *expulsion-type fuse* has an element which will melt and vaporize when it is overloaded, causing the power line it is connected in series with to open. *Liquid fuses* have a liquid-filled metal enclosure which contains the fuse element. The liquid acts as an arc suppressing medium. When the fuse element melts due to an excessive current in a power line, the element is immersed in the liquid to extinguish the arc. This type of fuse reduces the problem of high-voltage arcing. A *solid-material fuse* is similar to a liquid fuse except that the arc is extinguished in a chamber filled with solid material. High-voltage fuses are shown in Fig. 7-2.

Ordinarily, high-voltage fuses at substations are mounted adjacent to air-break disconnect switches. These switches provide a means of switching power lines and disconnecting them for repair. The fuse and switch enclosure is usually mounted near the overhead power lines at a substation.



Courtesy Square D Co

Fig. 7-2. High-voltage fuses.

High-Voltage Circuit Breakers

Circuit breakers which control high voltages are [illegible] located at electrical substations. Many outdoor [illegible] stations use oil-filled circuit breakers, such as the one shown in Fig. 7-3. In this type of circuit breaker, the contacts are immersed in an insulating oil contained in a metal enclosure. Another type of high-voltage circuit breaker is the magnetic air breaker in which the contacts separate, in the air, when the power line is overloaded. Magnetic blowout coils are used to develop a magnetic field which causes the arc, that is produced when the contacts break, to be concentrated into arc chutes where it is extinguished. A modification of this type is the compressed-air circuit breaker. In this type, a stream of compressed air is concentrated on the contacts when the power line is opened. The compressed air aids in extinguishing the arc which is developed when the contacts open. It should be pointed out that large arcs are present whenever a high-voltage circuit is

Fig. 7-3. An outdoor substation showing a high-voltage circuit breaker.

interrupted. This problem is not encountered to any great extent in low-voltage protective equipment.

There are two major types of high-voltage circuit breakers—oil-filled and oilless. These circuit breakers are designed to operate on voltages of 1000 volts to over 500,000 volts. Oil-filled circuit breakers are used primarily for outdoor substations, except for very high voltages in the range of 500,000 volts and higher. Oilless circuit breakers are ordinarily used for indoor operation.

High-Voltage Disconnect Switches

High-voltage disconnect switches are used to disconnect electrical equipment from the power lines which supply the equipment. Ordinarily, disconnect switches are not operated when current is flowing through them. A high-voltage arcing problem would occur if disconnect switches were opened while current was flowing through them. They are opened mainly to isolate equipment from power lines for safety purposes. Most disconnect switches are the "air-break" type which is similar in construction to knife switches. These switches are available for indoor or outdoor use in both manual and motor-operated designs. An air-break high-voltage disconnect switch is shown in the upper portion of Fig. 7-3.

Lightning Arresters

The purpose of using lightning arresters on power lines is to cause the conduction to ground of excessively high voltages that are caused by lightning strikes or other system problems. Without lightning arresters, power lines and associated equipment could become inoperable when struck by lightning. Arresters are designed to operate rapidly and repeatedly if necessary. Their response time must be more rapid than the other protective equipment used on power lines.

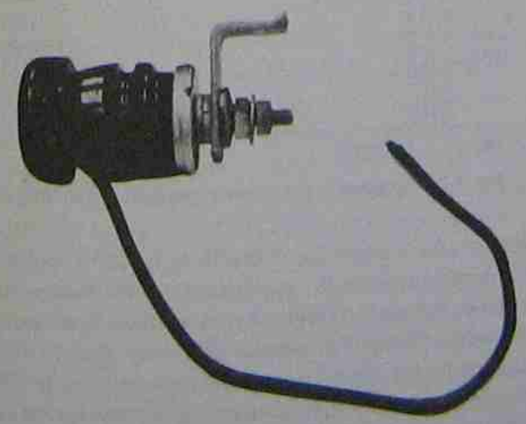


Fig. 7-4. A lightning arrester.

Lightning arresters must have a rigid connection to ground on one side. The other side of the arrester is connected to a power line. Sometimes, they are connected to transformers or the insides of switchgear. Lightning is a major cause of power-system failures and equipment damage, so lightning arresters have a very important function.

Lightning arresters are also used at outdoor substations. The lightning arrester, such as that shown in Fig. 7-4, is used to provide a path to ground for lightning strikes or hits. This path eliminates the flashover between power lines, which causes short circuits. Valve-type lightning arresters are used frequently. They are two-terminal devices in which one terminal is connected to the power line and the other is connected to ground. The path from line to ground is of such high resistance that it is normally open. However, when lightning, which is a very high voltage, strikes a power line, it causes conduction from line to ground. Thus, voltage surges are conducted to ground before flashover between the lines occurs. After the lightning surge has been conducted to ground, the valve assembly then causes the lightning arrester to become nonconductive once more.

High-Voltage Insulators

All power transmission lines must be isolated so as not to become safety hazards. Large strings of insulators are used at substations and at other points along the power distribution system to isolate the current-carrying conductors from their steel supports or any other ground-mounted equipment. Insulators may be made of porcelain, rubber, or a thermoplastic material. High-voltage insulators are shown in Fig. 7-5.

Power transmission lines require many insulators in order to electrically isolate the power lines from the steel towers and wooden poles which support the lines. Insulators must have enough mechanical strength to support power lines under all weather conditions. They must also have sufficient insulating properties to prevent any arcing between the power lines and their support structures. High-voltage insulators are usually made of porcelain. Insulators are constructed in "strings" which are suspended from steel or wooden towers. The design of these insulators is very important since design affects their capacitance and their ability to withstand weather conditions.

High-Voltage Conductors

The conductors used for power distribution are, ordinarily, uninsulated aluminum wires or aluminum-conductor steel-reinforced (ACSR) wires for long-distance transmission, and insulated copper wires for shorter distances. Cross-sectional areas of some typical

types of conductors that are used for high-voltage systems are shown in Fig. 7-6.

Voltage Regulators

Voltage regulators are an important part of the power distribution system. They are used to maintain the voltage levels at the proper value as a constant voltage must be maintained in order for the electrical equipment to function properly. For instance, motors do not

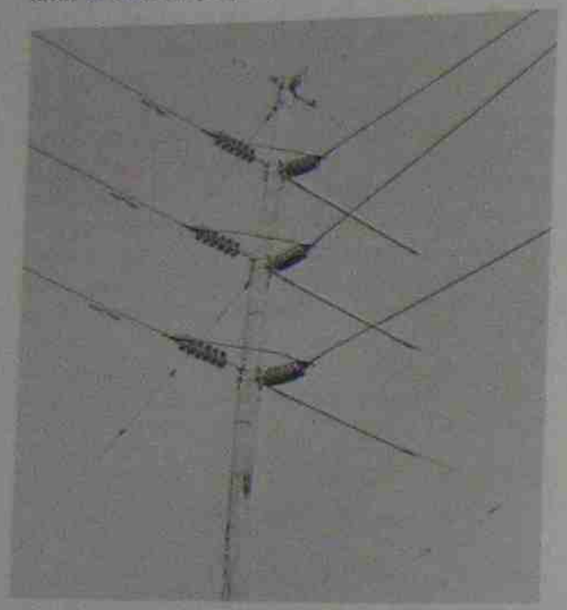


Fig. 7-5. High-voltage insulators.

operate properly when a reduced or an excessive voltage is applied to them. Transformer tap-changers, illustrated in Fig. 7-7, may be used as voltage regulators. By either manual or automatic changing the secondary tap, the voltage output can be changed to compensate for changes in the load voltage. As load current increases, line loss ($I \times R$) also increases. Increased line loss causes the secondary voltage (V_S) to decrease. If the secondary tap is initially connected to tap No. 4, the secondary voltage can be boosted by reconnecting to either tap No. 3, No. 2, or No. 1. This can be done automatically with a motor-controlled tap changer. There are various other types of automatic voltage regulators which can be used with electrical power distribution systems.

POWER-SYSTEM PROTECTIVE EQUIPMENT

There are many devices that are used to protect electrical power systems from damages due to abnormal conditions. For instance, switches, fuses, circuit breakers, lightning arresters, and protective relays are

Fig. 7-6. High-voltage conductors.

all used for this purpose. Some of these devices automatically disconnect the equipment from power lines before any damage can occur. Other devices sense changes from the normal operation of the system and make the changes necessary to compensate for abnormal circuit conditions. The most common electrical

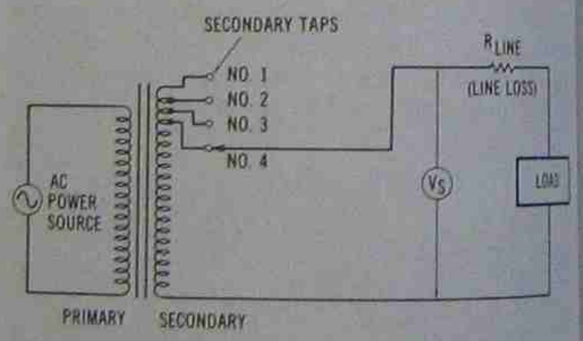
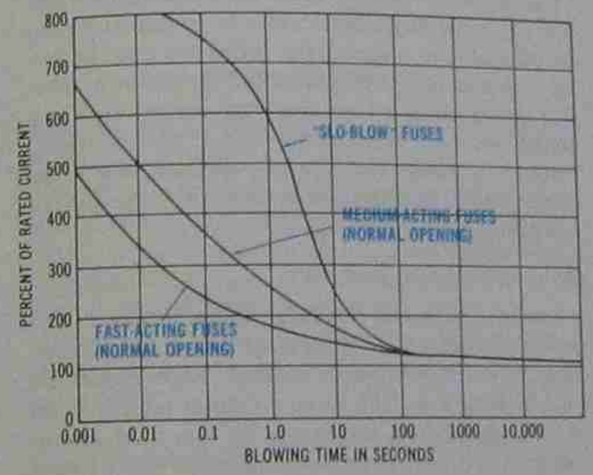


Fig. 7-7. Transformer tap-changer voltage regulator.

problem which requires protection is short circuits. Other problems include overvoltage, undervoltage, and changes in frequency. Generally, more than one method of protection is used to protect electrical circuits from faulty conditions. The purpose of any type of protective device is to cause a current-carrying conductor to become inoperative when an excessive amount of current flows through it.

Types of Fuses

The simplest type of protective device is a fuse. Fuses are low-cost items and have a fast operating speed. However, in three-phase systems, since each hot line must be fused, two lines are still operative if only one fuse burns out. Three-phase motors will continue to run with one phase removed. This condition is undesirable, in most instances, since motor torque is greatly reduced and overheating may result. Another obvious disadvantage of fuses is that replacements are required. All protective devices, including fuses, have an operating-characteristic time curve, such as the one shown in Fig. 7-8. To prevent any possible damage to equipment, circuit protection should be planned utilizing these curves. They show the response time required when an overload occurs for a protective device to interrupt a circuit.



Courtesy Littelfuse, Inc.

Fig. 7-8. Typical operating-characteristic time curves for three types of fuses.

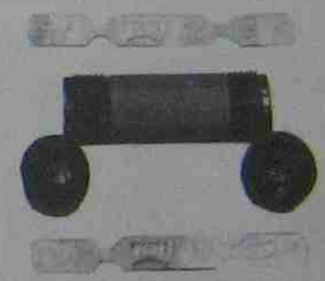
Plug Fuses—Fuses are used in safety switches and power distribution panels. The plug fuse, shown in Fig. 7-9A, is a common type of fuse. Standard sizes for this fuse are 10, 15, 20, 25, and 30 amperes at voltages of 125 volts or below. These fuses have a zinc or metallic-alloy-fusible element enclosed in a case made of an insulating material. Their most common use is in safety switches and fuse panelboards.

Cartridge Fuses—Cartridge fuses, such as the one shown in Fig. 7-9B, are commonly used in power distribution systems for voltages up to 600 volts. They have a zinc or alloy-fusible element which is housed in a round fiber enclosure. One type has a nonrenewable element, while another type, such as the one shown in Fig. 7-9C, has a renewable element. Cartridge fuses may be used to protect high-current circuits since they come in sizes of 60, 100, 200, 400, 600, and 1000 amperes.

Time-Lag Fuses—A modification of the plug or cartridge fuse is called a time-lag fuse. This type of fuse is used to delay the circuit-interrupting action. It is useful where momentary high currents exist periodically, such as motor-starting currents. The fuse element melts only when an excessive current is sustained over the time-lag period; thus, sufficient circuit protection is still provided.

(A) Plug fuses.

(B) Cartridge fuse.



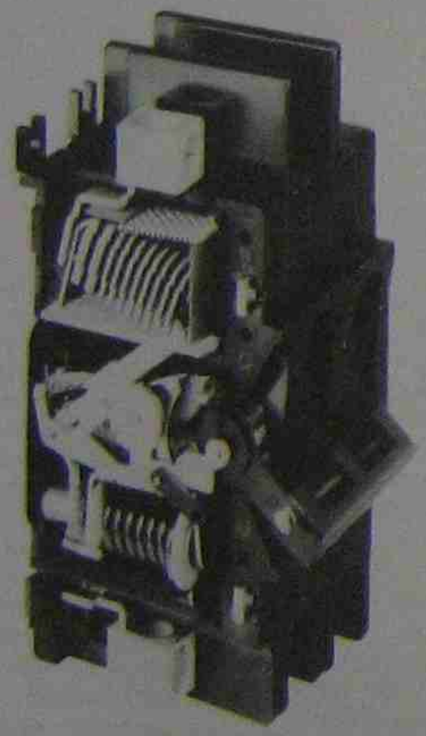
(C) Renewable-element fuse.

Fig. 7-9. Common types of fuses.

Fuse Metals—The type of metal used in fuses is ordinarily an alloy material or, possibly, aluminum. All metals have resistance, so when current flows through metal, heat energy is produced. As the current increases, more heat is produced, causing the temperature of the metal to increase. When the melting point of the fuse metal is reached, the fuse will open, causing the circuit to which it is connected to open. Metals which decompose rapidly are used rather than ones which produce small metallic globules when they melt. This reduces the likelihood of any arc-over occurring after the fuse metal has melted. The current rating of fuses depends upon the melting temperature of the fuse metal, as well as its shape, size, and the type of enclosure used.

Low-Voltage Circuit Breakers

Circuit breakers are somewhat more sophisticated overload devices than are fuses. Although their function is the same as that of fuses, circuit breakers are much more versatile. In three-phase systems, circuit breakers can open all three hot lines when an overload occurs. They may also be activated by remote-control relays. Relay systems may cause circuit breakers to open due to changes in frequency, voltage, current, or other circuit variables. The internal construction of a circuit breaker is shown in Fig. 7-10. The circuit breakers used in industrial plants are usually of the low-voltage variety (less than 600 volts) and are not nearly as complex as their high-voltage counterparts (which were discussed previously). Most low-voltage circuit breakers are housed in molded-plastic cases which mount in metal power distribution panels. Circuit breakers are designed so that they will automatically open when a current occurs which exceeds the rating of the breaker. Ordinarily, the circuit breakers must be reset manually. Most circuit breakers employ either a thermal tripping element or a magnetic trip element. Ratings of circuit breakers extend into current ranges that are as high as 800 to 2000 amperes.



Courtesy Airpax Electronics, Inc.

Fig. 7-10. Internal construction of a circuit breaker.

Protective Relays

Protective relays provide an accurate and sensitive method of protecting electrical equipment from short circuits and other abnormal conditions. Overcurrent relays are used to cause the rapid opening of electrical power lines when the current exceeds a predetermined value. The response time of the relays is very important in protecting the equipment from damage. Some common types of faults which may be protected by relays are line-to-ground short circuits, line-to-line short circuits, double line-to-ground short circuits, and three-phase line short circuits. Each of these conditions is caused by faulty circuit conditions which draw abnormally high current from the power lines.

Motor-Fault Current Protection

Motor-fault currents are excessive currents which occur in motors due to some unnatural malfunction. Since motor-fault currents cannot be withstood for any duration of time, some type of protection must be provided to disconnect the motor from the power distribution system when a fault condition occurs. Such protection may be provided by motor starters, circuit breakers, or fuses. The type of protection used is dependent upon several characteristics of the power distribution system and the motor.

Motor Protective Devices

The distribution of electrical power to motors is a particularly important function of industrial and commercial power distribution systems. Since motors are used in some way with most industrial processes, the efficient distribution of energy to industrial electric motors is very important. Basic functions which motors are expected to perform are starting, stopping, reversing, and speed variation. These functions may be manually or automatically controlled. Various types of

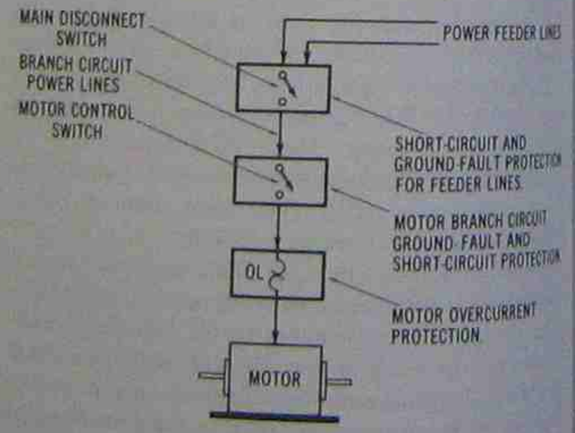


Fig. 7-11. Block diagram of a motor-protection circuit.

Courtesy Furnas Electric Co.

Fig. 7-12. Bimetal overload relay.

protective devices are used to provide for the efficient distribution of power to electric motors.

Overload protection is the most important motor protection function. Such protection should serve the motor, its branch circuit, and associated control equipment. The major cause of motor overload is an excessive mechanical load on the motor which causes it to draw too much current from the power source. A block diagram of a motor protection system is shown in Fig. 7-11.

Courtesy Square D Co.

Fig. 7-13. Thermal overload relays (melting-alloy type).

Thermal overload relays are often used as protective devices. Thermal relays may be reset either manually or automatically. One type of thermal overload relay, shown in Fig. 7-12, uses a bimetallic heater element. The bimetallic element bends as it is heated by the current flowing through it. When the current reaches the rating of the element, the relay opens the branch circuit. Another type of element is the melting-alloy type shown in Fig. 7-13. This device has contacts held closed by a ratchet wheel. At the current capacity of the device, the fusible alloy melts causing the ratchet wheel to turn. A spring then causes the device to open the circuit.

Overheating Protection for Motors

Motors must be protected from excessive overheating. This protection is provided by magnetic or thermal protective devices which are ordinarily within the motor-starter enclosure. Protective relays or circuit breakers can also perform this function. When an operational problem causes the motor to overheat, the protective device is used to automatically disconnect the motor from its power supply.

Undervoltage Protection

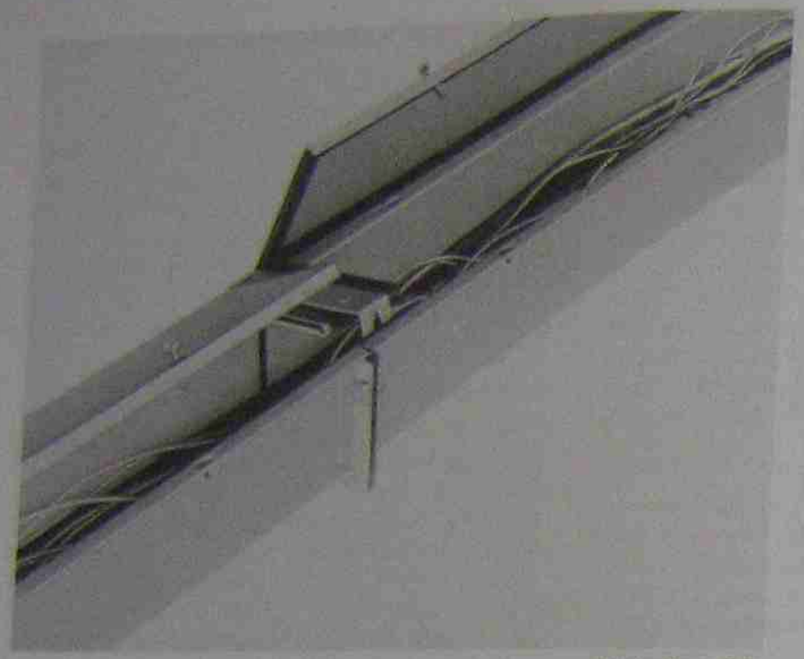
Motors do not operate efficiently when less than their rated voltage is applied and some types of motors can be destroyed if they are operated continuously at reduced voltages. Magnetic contactors (see Chapter 9) may be used effectively to protect against undervoltages. A specific level of voltage is required to cause magnetic contactors to operate. If the voltage is reduced below a specified level, the magnetic contactor will open, thus disconnecting the circuit between the power source and the motor and stopping the motor before any damage can be done.

POWER DISTRIBUTION INSIDE INDUSTRIAL AND COMMERCIAL BUILDINGS

Electrical power is delivered to the location where it is to be used and then distributed within a building by the power distribution system. Various types of circuit breakers and switchgear are employed for power distribution. Another factor involved in power distribution is the distribution of electrical energy to the many types of loads which are connected to the system. This part of the distribution system is concerned with the conductors, feeder systems, branch circuits, grounding methods, and protective and control equipment which is used.

Raceways

Most electrical distribution to industrial and commercial loads is through wires and cables contained in raceways. These raceways carry the conductors which carry the power to the various equipment throughout a building. Copper conductors are ordinarily used for indoor power distribution. The physical size of each conductor is dependent upon the current rating of the branch circuit. Raceways may be large metal ducts, such as those shown in Fig. 7-14, or rigid metal conduit. These raceways provide a compact and efficient method of routing cables, wires, etc., throughout an industrial complex.



Courtesy Square D Co.

Fig. 7-14. A typical metallic raceway.

Feeder Lines and Branch Circuits

The conductors which carry current to the electrical load devices in a building are called *feeders* and *branch circuits*. Feeder lines supply power to branches which are connected to them. Primary feeder lines may be either overhead or underground. Usually, overhead lines are preferred because they permit flexibility for future expansion. Underground systems cost more, but they are much more attractive in appearance. Secondary feeders are connected to the primary feeder lines and supply power to individual sections within the building. Either aluminum or copper feeder lines may be used, depending on the specific power requirements. The distribution is from the feeder lines, through individual protective equipment, to branch circuits which supply the various loads. Each branch circuit has various protective devices according to the needs of that particular branch. The overall feeder-branch system may be a very complex network of switching equipment, transformers, conductors, and protective equipment.

Switching Equipment

In addition to circuit protection, power distribution systems must have equipment which can be used to connect or disconnect the entire system or parts of the system. Various types of switching devices are used to perform this function. A simple type of switch is the *safety switch*. This type of switch is mounted in a metal enclosure and operated by means of an external handle.

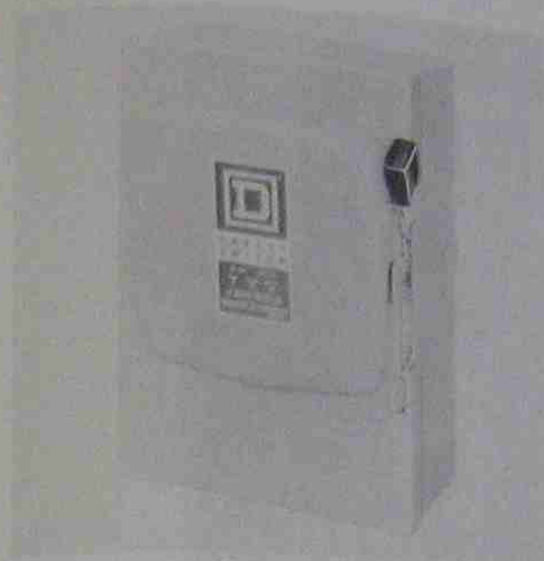
A three-phase safety switch is shown in Fig. 7-16 while a single-phase safety switch is shown in Fig. 7-17. Safety switches are used only to turn a circuit off or on; however, fuses are often mounted in the same enclosure with the safety switch.

Distribution Panelboards

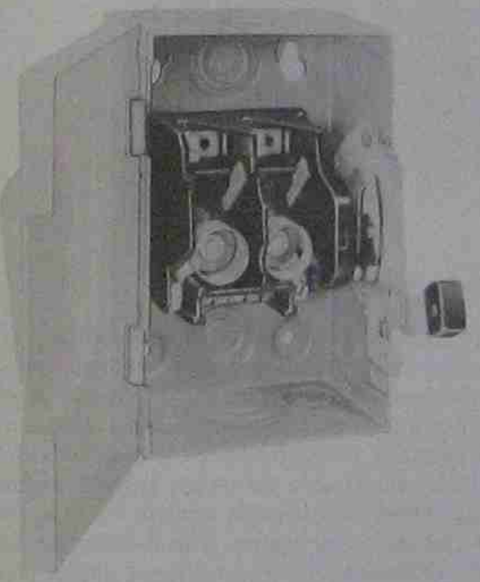
Another type of switch is the kind used in conjunction with a circuit-breaker panelboard. Panelboards are metal cabinets which enclose the main disconnect switch and the branch-circuit protective equipment. Distribution panelboards are usually located between the power feed lines within a building and the branch circuits which are connected to it. A typical distribution panelboard is shown in Fig. 7-17.

Low-Voltage Switchgear

Metal-enclosed low-voltage switchgear is used in many industrial and commercial buildings. These are used as a distribution control center to house the circuit breakers, bus bars, and terminal connections which are part of the power distribution system. Ordinarily, a combination of switchgear and distribution transformers is placed in adjacent metal enclosures, such as that shown in Fig. 7-18. This combination is referred to as a load-center unit substation since it is the central control for several loads. The rating of these load centers is usually 15,000 volts or lower for the high-voltage section and 600 volts or less for the low-voltage section. Load centers provide flexibility in the electrical



(A) Exterior view.



(B) Interior view.

Courtesy Square D Co.

Fig. 7-15. A single-phase safety switch.

power distribution design of industrial plants and commercial buildings.

Metal-enclosed switchgear or metal-clad switchgear is a type of equipment which houses all the necessary control devices for the electrical circuits that are connected to them. The control devices contained inside the switchgear include circuit breakers, disconnect switches, interconnecting cables and buses, transformers, and the necessary measuring instruments. Switchgear is used for indoor and outdoor applications at industrial plants, commercial buildings, and at substations. The voltage ratings of switchgear are ususally from 13.8 to 138 kilovolts with 1 megavolt-ampere to 10 megavolt-ampere power ratings.

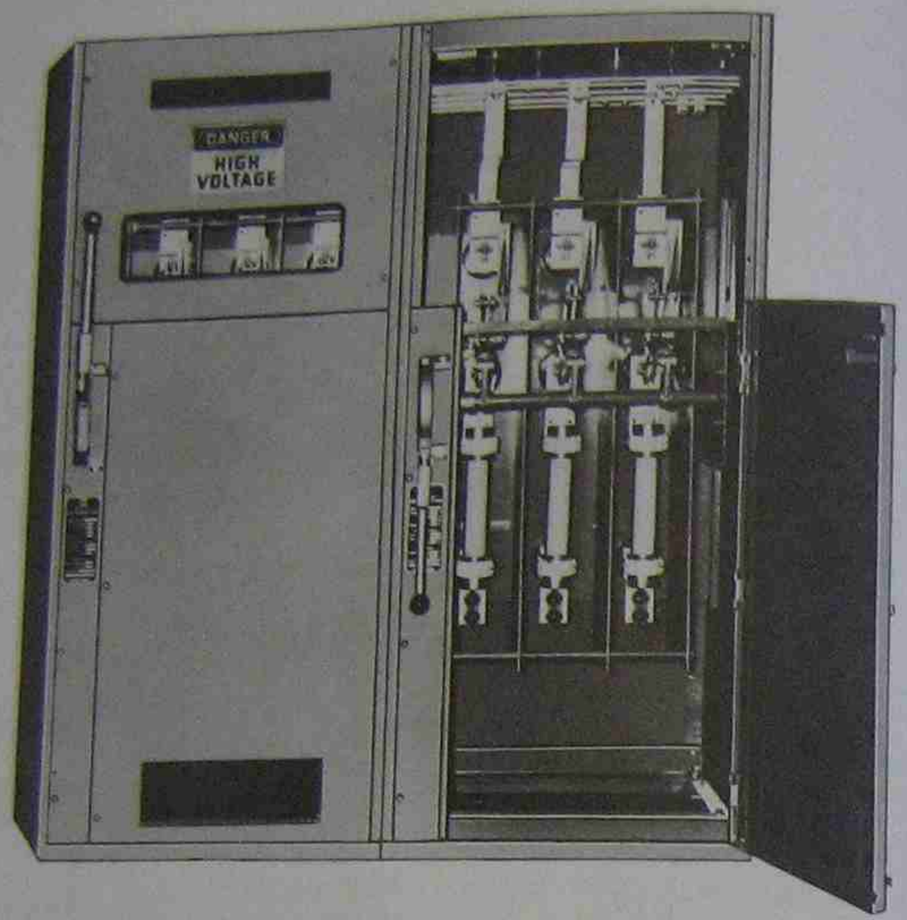
THE ELECTRICAL SERVICE ENTRANCE

Electrical power is brought from the overhead power lines or from the underground cable into a building by what is called a *service entrance*. A good working knowledge of the National Electrical Code (NEC) specifications and definitions is necessary to understand service-entrance equipment. The NEC sets the minimum standards that are necessary for a wiring design inside a building.

Courtesy Square D Co.

Fig. 7-16. Interior view of a three-phase safety switch.

The type of equipment used for an electrical service entrance of a building may include high-current conductors and insulators, disconnect switches, protective equipment for each load circuit which will be connected to the main power system and the meters needed to measure power, voltage, current, or frequency. It is also necessary to ground the power system at the service-entrance location. This is done by a "grounding electrode" which is a metal rod driven deep into the ground. The grounding conductor is attached securely to this grounding electrode. Then, the grounding conductor is used to make contact with all neutral conductors and safety grounds of the system.



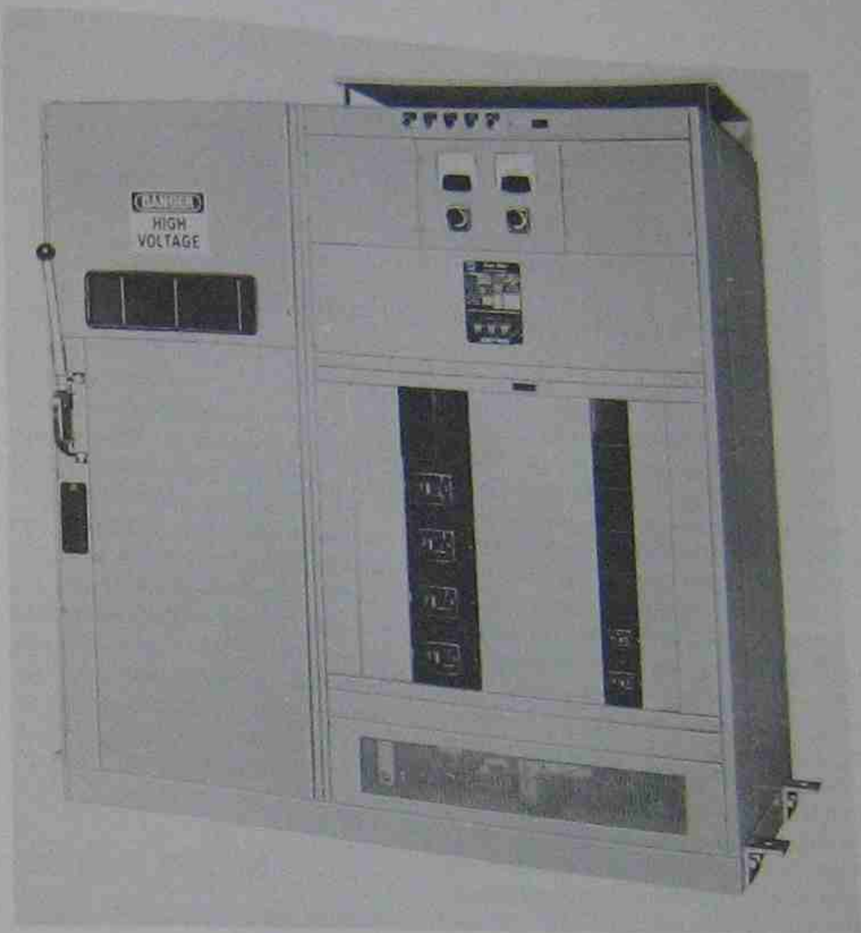
Courtesy Square D Co.

Fig. 7-17. A typical power distribution panelboard.

SERVICE-ENTRANCE TERMINOLOGY

There are several terms associated with service-entrance equipment. The *service-entrance conductors* are a set of conductors which are brought to a building by the local electrical utility company. These conductors must be capable of carrying all of the electrical current that is to be delivered to the various loads inside the building which are to be supplied by the power system. Conductors which extend from the service entrance to a power distribution panel or other type of overcurrent protective equipment are called *feeders*. Feeders are power lines which supply branch circuits. A *branch circuit* is defined as conductors which extend beyond the last overcurrent protective equipment of the power system. Usually, each branch circuit delivers electrical power to a small percentage of the total load of the main power system.

In commercial and industrial installations, *switchboards* and *panelboards* are used to supply power to various loads throughout the power system. A switchboard is a large enclosure which has several overcurrent protective devices (fuses or circuit breakers). Each feeder is connected to the proper type of overcurrent device. Often, switchboards contain metering equipment for the power system. Panelboards are smaller than switchboards but are used for a similar purpose. They are enclosures for overcurrent devices for either branch circuits or feeder circuits. A common example of a panelboard is the main power-distribution panel which houses the circuit breakers used for the branch circuits of a home. For more specific definitions of terms, you should refer to the most recent edition of the National Electrical Code.



Courtesy Square D Co.

Fig. 7-18. A typical load-center unit substation.

CHAPTER 8

Single-Phase and Three-Phase Systems

When electrical power is distributed to its point of utilization, it is normally either in the form of single-phase or three-phase ac voltage. Single-phase ac voltage is distributed into residences and other smaller commercial buildings. Normally, three-phase ac voltage is distributed to industries and larger commercial buildings. Thus, the main types of power distribution systems are residential (single-phase) and industrial or commercial (three-phase).

An important aspect of both single-phase and three-phase distribution systems is grounding. Two grounding methods, system grounding and equipment grounding, will be discussed, along with ground-fault protective equipment.

SINGLE-PHASE SYSTEMS

Most electrical power when produced at the power plants is produced as three-phase ac voltage. Electrical power is also transmitted in the form of three-phase voltage over long-distance power-transmission lines. At its destination, three-phase voltage can be changed into three separate single-phase voltages for distribution into the residential areas.

Although single-phase systems are used mainly for residential power distribution systems, there are some industrial and commercial applications of single-phase systems. Single-phase power distribution usually originates from three-phase power lines so electrical power systems are capable of supplying both three-phase and single-phase loads from the same power lines. Fig. 8-1 shows a typical power distribution system—from the power station (source) to the various single-phase and three-phase loads which are connected to the system.

Single-phase systems can be of two major types—single-phase two-wire systems or single-phase three-wire systems. A single-phase two-wire system is shown in Fig. 8-2A (the top diagram). This system uses a 10-kVA transformer whose secondary produces one single-phase voltage, such as 120 or 240 volts. This system has one hot line and one neutral line. In residential distribution systems, several years ago, this was the most used type to provide 120-volt service. However, as appliance power requirements increased, the need for a dual-voltage system was evident.

To meet the demand for more residential power, the single-phase three-wire system is now used. A home-service entrance can be supplied with 120/240-volt energy by the methods shown in Figs. 8-2B and 8-2C (center and bottom diagrams). Each of these systems is derived from a three-phase power line. The single-phase three-wire system has two hot lines and a neutral line. The hot lines, whose insulation is usually black and red, are connected to the outer terminals of the transformer secondary windings. The neutral (white insulated wire) is connected to the center tap of the distribution transformer. Thus, from neutral to either hot line, 120 volts for lighting and small-power requirements may be obtained. Across the hot lines, 240 volts is supplied for higher-power requirements. Therefore, the current requirement for large power-consuming equipment is cut in half, since 240 volts rather than 120 volts is used. Either the single-phase two-wire or the single-phase three-wire system can be used to supply single-phase power for industrial or commercial use. However, these single-phase systems are mainly for residential power distribution.

THREE-PHASE SYSTEMS

Since industries and commercial buildings use three-phase power predominantly, they rely upon three-phase distribution systems to supply this power. Large three-phase distribution transformers are usually located at substations adjoining the industrial plants or commercial buildings. Their purpose is to supply the proper ac voltages to meet the necessary load requirements. The ac voltages that are transmitted to the distribution substations are high voltages which must be stepped down by three-phase transformers.

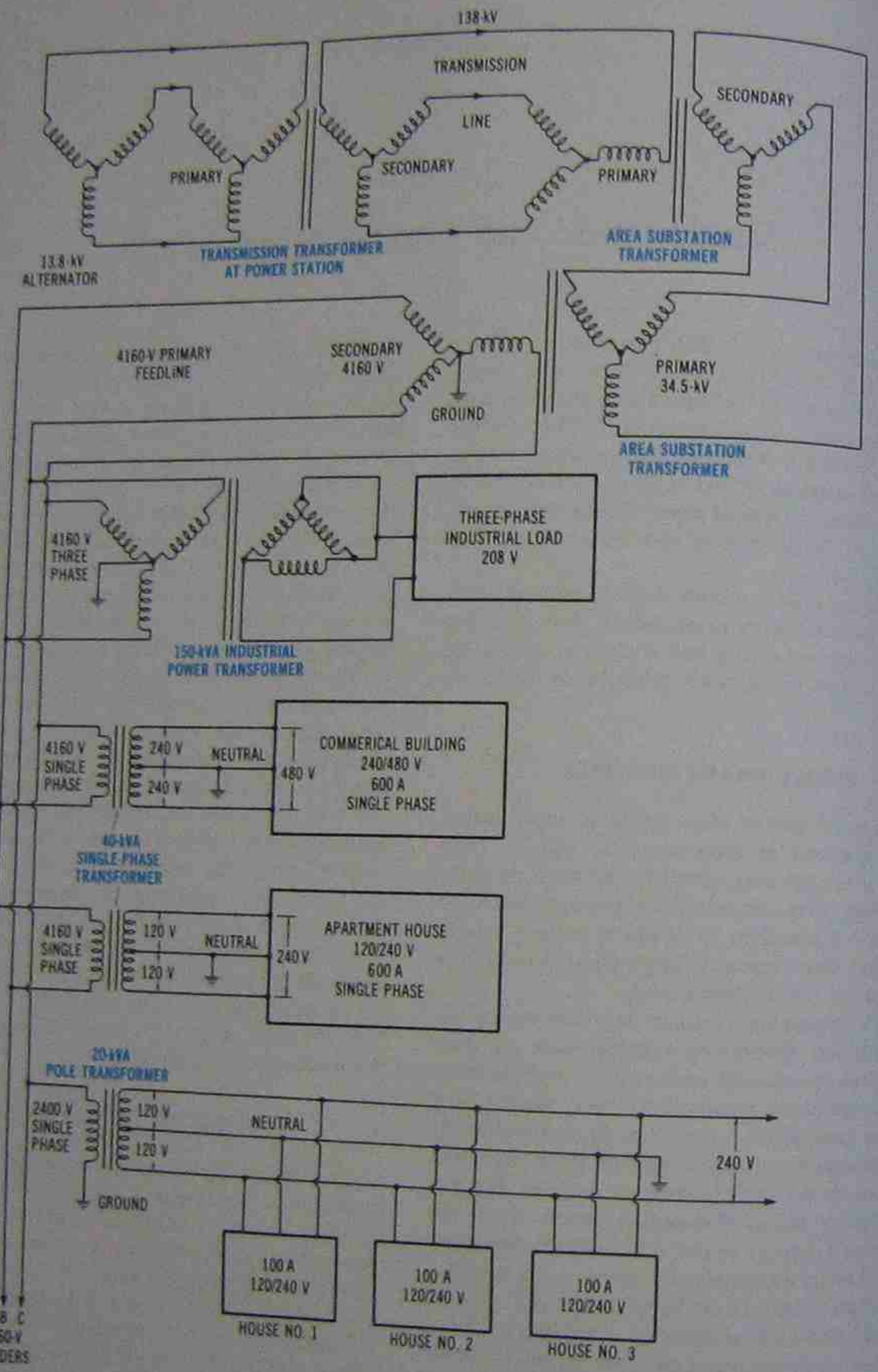
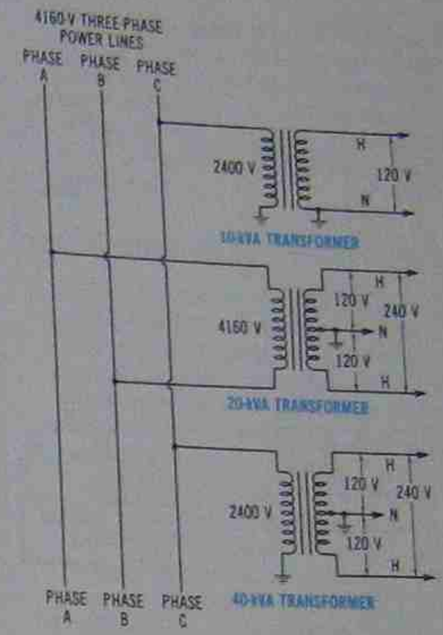


Fig. 8-1. A typical power distribution system.



(A) Single-phase, two-wire system.

(B) Single-phase, three-wire system.

(C) Single-phase, three-wire system.

Fig. 8-2. Single-phase power distribution systems.

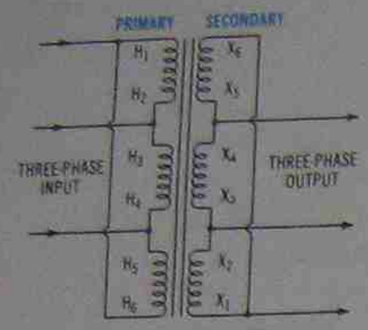
Three-Phase Transformer Connections

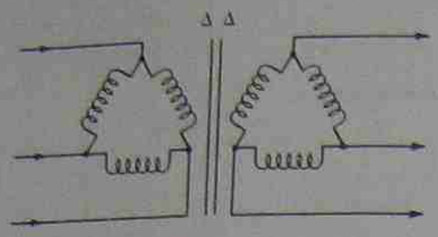
There are five ways in which the primary and secondary windings of three-phase transformers may be connected. These are the delta-delta, the delta-wye, the wye-wye, the wye-delta, and the open-delta connections. These basic methods are illustrated in Fig. 8-3. The delta-delta connection (Fig. 8-3A) is used for some lower voltage applications. The delta-wye method (Fig. 8-3B) is commonly used for stepping up voltages since an inherent step-up factor of 1.73 times is obtained due to the voltage characteristic of the wye-connected secondary. The wye-wye connection of Fig. 8-3C is ordinarily not used, while the wye-delta method (Fig. 8-3D) may be used advantageously to step voltages down. The open-delta connection (Fig. 8-3E) is used if one transformer winding becomes damaged or is taken out of service. The transformer will still deliver three-phase power, but at a lower current and power capacity. This connection may also be desirable when the full capacity of three transformers is not needed until a later time. Two identical single-phase transformers can be used to supply power to the load until, at a later time, the third transformer is needed to meet increased load requirements.

Types of Three-Phase Systems

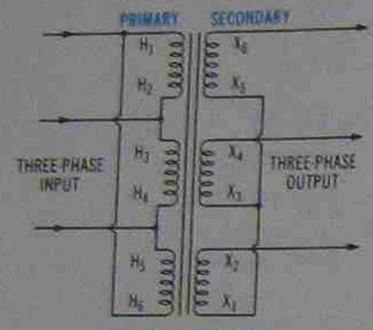
Three-phase power distribution systems which supply industrial and commercial buildings are classified according to the number of phases and number of wires required. These systems, shown in Fig. 8-4, are the three-phase three-wire system, the three-phase three-wire system with neutral, and the three-phase four-wire system. The primary winding connection is not considered here. The three-phase three-wire system, shown in Fig. 8-4A, can be used to supply motor loads of 240 volts or 480 volts. Its major disadvantage is that it only supplies one voltage as only three hot lines are supplied to the load. The usual insulation color code for these hot lines is black, red, or blue, as specified in the National Electrical Code.

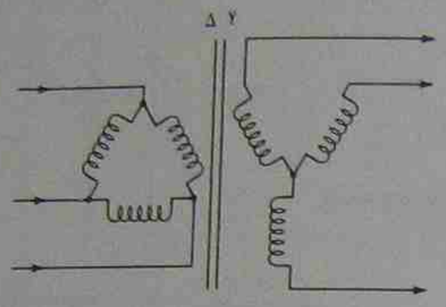
The disadvantage of the three-phase three-wire system may be partially overcome by adding one center-tapped phase winding as shown in the three-phase three-wire with neutral system of Fig. 8-4B. This system can be used as a supply for 120/240 volts or 240/480 volts. Assume that it is used to supply 120/240 volts. The voltage from the hot line at point 1 and the hot line at point 2 to neutral would be 120 volts, due to the center-tapped winding. However, 240 volts would still be available across *any* two hot lines. The neutral wire is color coded with a white or gray insulation. The disadvantage of this system is that, when making wiring changes, it would be possible to connect a 120-volt load between the neutral and point 3 (sometimes called the "wild" phase). The voltage present here would be the combination of three-phase voltages between points 1 and 4 and points 1 and 3. This would be a voltage in



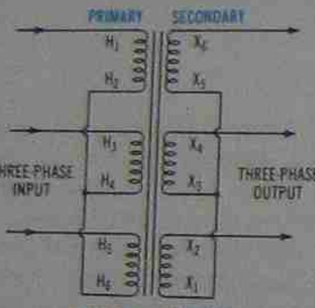


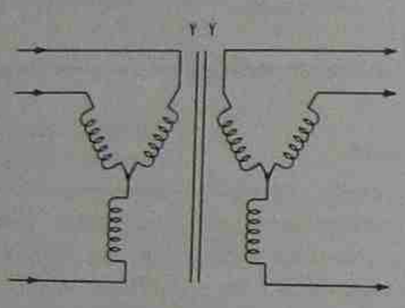
(A) The delta-delta connection.



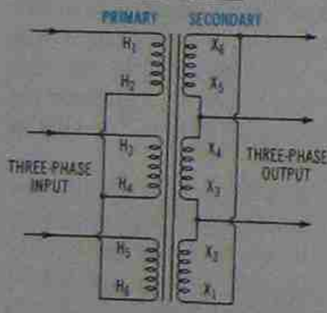


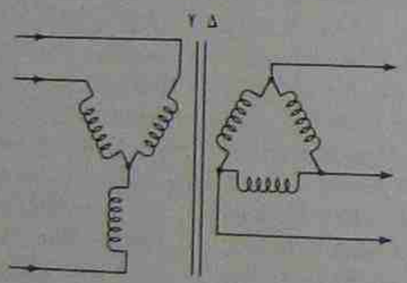
(B) The delta-wye connection.



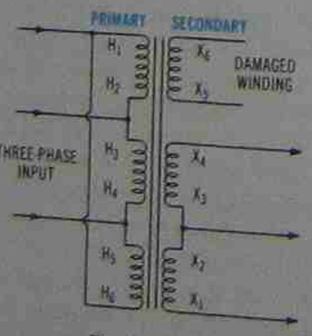


(C) The wye-wye connection.



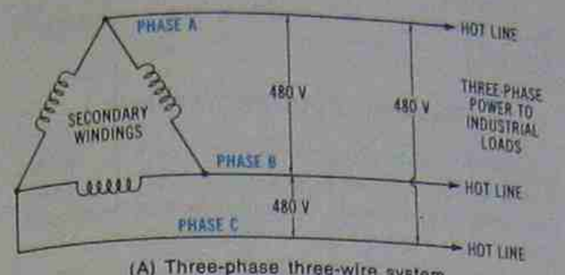


(D) The wye-delta connection.

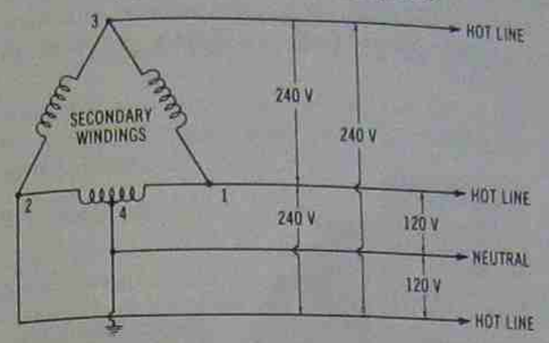


(E) The open-delta connection.

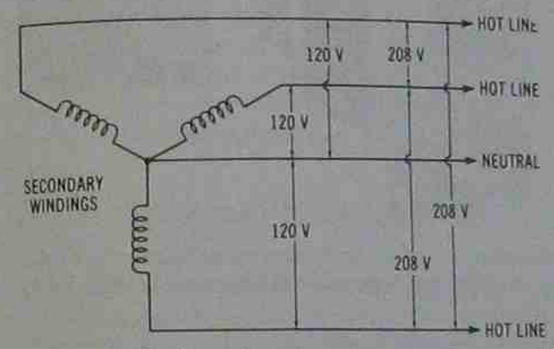
Fig. 8-3. Basic three-phase transformer connection methods.



(A) Three-phase three-wire system.



(B) Three-phase three-wire system with neutral.



(C) Three-phase four-wire system.

Fig. 8-4. Industrial power distribution systems.

excess of 300 volts! Although the "wild-phase" situation exists, this system is capable of supplying both high-power loads and low-voltage loads, such as for lighting and small equipment.

The most widely used three-phase power distribution system is the three-phase four-wire system. This system, shown in Fig. 8-4C, commonly supplies 120/208 volts and 277/480 volts for industrial or commercial load requirements. The 120/208-volt system is illustrated here. From neutral to any hot line, 120 volts for lighting and low-power loads may be obtained. Across any two hot lines, 208 volts is present for supplying motors or other high-power loads. The most popular system for industrial and commercial power distribution is the 277/408-volt system which is capable of supplying both three-phase and single-phase loads. A 240/416-volt system is sometimes used for industrial loads, while the 120/208-volt system is often used for underground distribution in urban areas. Note that this system is based on the voltage characteristics of the three-phase wye connection and that the relationship $V_L = V_P \times 1.73$ exists for each application of this system.

GROUNDING OF DISTRIBUTION SYSTEMS

The concept of grounding in an electrical power distribution system is very important. Distribution systems must have continuous uninterrupted grounds. If a grounded conductor is opened, the ground is no longer functional. An open-ground condition could present severe safety problems and cause abnormal system operation.

Distribution systems must be grounded at substations and at the end of the power lines—before the power is delivered to the load. Grounding is necessary at substations for the safety of the public and the power-company maintenance personnel. Grounding also provides points for transformer neutral connections for equipment grounds. Safety and equipment grounds will be discussed in more detail later.

At substations, all external metal parts must be grounded and all transformer, circuit breaker, and switch housings must be grounded. Also, metal fences and any other metal which is part of the substation construction must be grounded. Grounding assures that any person who touches any of the metal parts will not receive a high-voltage shock. Therefore, if a high-voltage line were to come in contact with any of the grounded parts, the system would be opened by protective equipment. Thus, the danger of high voltages at substations is substantially reduced by grounding. The actual ground connection is made by welding, brazing, or bolting a conductor to a metal rod or bar which is then physically placed in the earth. This rod device is called a grounding electrode. Proper grounding techniques are required for safety as well as circuit performance. There are two types of grounding: (1) system grounding and (2) equipment grounding. Another important grounding factor is ground-fault protective equipment.

System Grounding

System grounding involves the actual grounding of a current-carrying conductor (usually called the neutral) of a power distribution system. Three-phase systems may be either the wye or delta type. The wye system has an obvious advantage over the delta system since one side of each phase winding is connected to ground. We will define a ground as a reference point

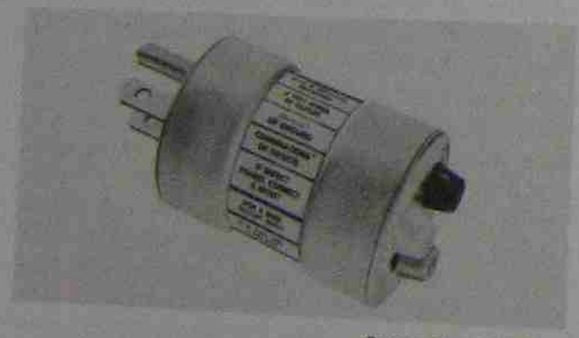
of zero-volt potential, which is usually an actual connection to earth ground. The common terminals of the wye system, when connected to ground, become the neutral conductor of the three-phase four-wire system.

The delta system does not readily lend itself to grounding since it does not have a common neutral. The problem of ground faults (line-to-ground shorts) occurring in ungrounded delta systems is much greater than in wye systems. A common method of grounding a delta system is to use a wye-delta transformer connection and ground the common terminals of the wye-connected primary. However, the wye system is now used more often for industrial and commercial distribution since the secondary is easily grounded and it provides overvoltage protection from lightning or line-to-ground shorts.

Single-phase 120/240- or 240/480-volt systems are grounded in a manner similar to a three-phase ground. The neutral of the single-phase three-wire system is grounded by a metal rod (grounding electrode) driven into the earth at the transformer location. System grounding conductors are insulated with white or gray material for easy identification.

Equipment Grounding

The second type of ground is the equipment ground which, as the term implies, places operating equipment at ground potential. The conductor which is used for this purpose is either bare wire or a green insulated wire. The National Electrical Code describes conditions which require fixed electrical equipment to be



Courtesy Circle F Industries

Fig. 8-5. A plug-in ground tester.

grounded. Usually all fixed electrical equipment located in industrial plants or commercial buildings should be grounded. Types of equipment that should be grounded include enclosures for switching and protective equipment for load control, transformer enclosures, electric motor frames, and fixed electronic test equipment. Industrial plants should use 120-volt single-phase duplex receptacles of the grounded type for all portable tools. The grounding of these receptacles may be checked by using a plug-in tester such as the one shown in Fig. 8-5.

GROUND-FAULT PROTECTION

Ground-fault interrupters (GFIs), such as the one shown in Fig. 8-6, are now used extensively in industrial, commercial, and residential power distribution systems. It is required by the National Electrical Code that all 120-volt single-phase 15- or 20-ampere receptacle outlets which are installed outdoors or in bathrooms have ground-fault interrupters connected to them.

Courtesy Leviton Manufacturing Co., Inc.

Fig. 8-6. A ground-fault interrupter (GFI).

GFI Operation

These devices are designed to eliminate electrical shock hazards resulting from individuals coming in contact with a hot ac line (line-to-ground short). The circuit interrupter is designed to sense any change in circuit conditions, such as would occur when a line-to-ground short exists. One type of GFI has control wires which extend through a magnetic toroidal loop (see Fig. 8-7). Ordinarily, the ac current flowing through the conductors inside the loop is equal in magnitude and opposite in direction. Any change in this equal and opposite condition is sensed by the magnetic toroidal loop. When a line-to-ground short occurs, an instantaneous change in circuit conditions occurs. The change causes a magnetic field to be induced into the toroidal loop. The induced current is amplified to a level sufficient to cause the circuit-breaker mechanism to open. Thus, any line-to-ground short will cause the ground-fault interrupter to open. The operating speed

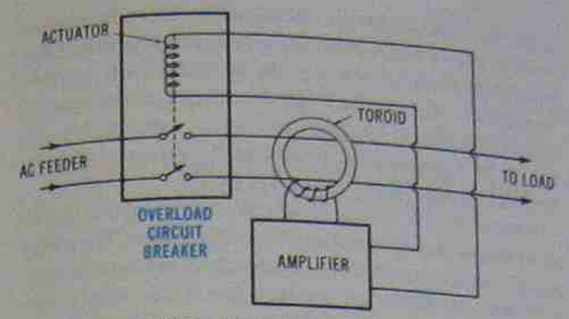


Fig. 8-7. Simplified schematic of a ground-fault interrupter.

of the GFI is so fast, since only a minute current opens the circuit, that the shock hazard to individuals is greatly reduced.

GFI Applications

Construction sites, where temporary wiring is set up, are required to use GFIs for the protection of workers using electrical equipment. Ground-fault protection of individuals and commercial equipment must be provided for wye-connected systems of 150 to 600 volts for each distribution panelboard rated at over 1000 amperes. In this situation, the GFI will open all ungrounded conductors at the panelboard when a line-to-ground short occurs. Now, GFIs are used for all types of residential, commercial, and industrial applications.

Types of Ground-Fault Protection Systems

There are four basic types of ground-fault protection systems in use today. They are hospital applications, residential applications, motor protection applications, and specific electrical power distribution system applications. These ground-fault systems can be classified either by what they are to protect or the type of protection they are to provide. Hospital applications and residential applications are designed to protect people from excessive shock. The motor and electrical power applications are for protecting electrical equipment.

Another classification method is according to the amount of current required before an alarm system sounds or the disconnect of an electrical circuit occurs. Typical current values that will cause alarms or disconnects to activate are 0.002 amperes (2 mA) for hospital applications, 0.005 amperes (5 mA) for residential applications, 5 to 100 amperes for motor-protective circuit applications, and 200 to 1200 amperes for electrical power distribution equipment applications.

Need for Ground-Fault Protection

In order to understand the need for a ground-fault circuit interrupter (for the protection of people), certain basic facts must first be understood. These facts relate to people as well as to ground faults.

One important fact is that a person's body resistance varies with the amount of moisture present on the skin, the muscular structure of the body, and the voltage to which the body is subjected. Experiments have shown that the body resistance from one hand to the other hand is somewhere between 1000 and 4000 ohms. These estimates are based upon several assumptions concerning moisture and muscular structure. We also know that resistance of the body (hand-to-hand) is lower for higher voltages. This is because higher voltages have the capability of "breaking down" the outer layers of the skin. Thus, higher voltages are more dangerous.

We can use Ohm's law to estimate that the typical current resulting from the average body resistance (from hand to hand) is about 115 mA at 240 volts ac and about 40 mA at 120 volts ac. The effects of a 60-Hz alternating current on the human body are generally accepted to be as given in Table 8-1.

Table 8-1. Body Reaction to Alternating Current

Amount of Current	Effect on Body
1 mA or less	No sensation (not felt).
More than 5 mA	Painful shock.
More than 10 mA	Muscle contractions; could cause a "freezing" to the electrical circuit for *some* people.
More than 15 mA	Muscle contractions; could cause "freezing" to the electrical circuit for *most* people.
More than 30 mA	Breathing difficult; could cause unconsciousness.
50 to 100 mA	Ventricular fibrillation of the heart is possible.
100 to 200 mA	Ventricular fibrillation of the heart is certain.
Over 200 mA	Severe burns and muscular contractions; the heart is more apt to stop beating than to fibrillate.
1 ampere and above	Permanent damage to body tissues.

Ventricular fibrillation is a contraction of the heart. Once ventricular fibrillation occurs, it will continue and death will occur within a few minutes. Resuscitation techniques, when applied immediately, could save a victim. Deaths caused by electrical shock account for a high percentage of the deaths which occur in the home and in industry. Many of these deaths are due to contact with low-voltage circuits (600 volts and under), mainly 120- and 240-volt systems.

Ground-Fault Protection for the Home

Ground-fault interruptors for homes consist of three types: (1) circuit breaker, (2) receptacle, and (3) plug-in types. Ground-fault protection devices are constructed according to standards developed by the Underwriter's Laboratories. The GFI circuit breakers combine ground-fault protection and circuit interruption in the same overcurrent and short-circuit protective equipment as does a standard circuit breaker. A GFI circuit breaker fits the same space required by a standard circuit breaker. It provides the same branch-circuit wiring protection as the standard circuit breaker, as well as ground-fault protection. The GFI sensing system continuously monitors the current balance in the ungrounded (hot) conductor and the grounded (neutral conductor. The current in the neutral wire becomes less than the current in the hot wire when a ground fault develops. This means that a portion of the circuit current is returning to ground by some means other than the neutral wire. When an imbalance in current occurs, the sensor (a differential current transformer) sends a signal to the solid-state circuitry which activates a trip mechanism. This action opens the hot line. A differential current as low as 5 mA will cause the sensor to send a fault signal and cause the circuit breaker to interrupt the circuit.

Ordinarily, GFI receptacles provide ground-fault protection on 120-, 208-, or 240-volt ac systems. The GFI receptacles come in 15- and 20-ampere designs. The 15-ampere unit has a receptacle configuration for use with 15-ampere plugs only. The 20-ampere device has a receptacle configuration for use with either 15- or 20-ampere plugs. These GFI receptacles have connections for hot, neutral, and ground wires. All GFI receptacles have a two-pole tripping mechanism which breaks both the hot and the neutral load connections at the time a fault occurs.

The plug-in GFI receptacles provide protection by plugging into a standard wall receptacle. Some manufacturers provide units which will fit either two-wire or three-wire receptacles. The major advantage of this type of unit is that it can be moved from one location to another.

Ground-Fault Protection for Power Distribution Equipment

Ground faults can destroy electrical equipment if allowed to continue. Phase-to-phase short circuits and some types of ground faults are usually high current. Normally, they are adequately handled by conventional overcurrent protective equipment. However, some ground faults produce an arcing effect from relatively low currents that are not large enough to trip conventional protective devices. Arcs can severely burn electrical equipment. A 480- or 600-volt system is more susceptible to arcing damage than a 120-, 208-, or 240-volt system due to the higher voltages which sustain the arcing effect. High-current faults are quickly detected by conventional overcurrent devices. Low-current values must be detected by GFIs.

Ground faults which cause an arcing in the equipment are probably the most frequent faults. They may result from damaged or deteriorated insulation, dampness, moisture, or improper connections. They usually occur between one hot conductor and the grounded equipment enclosure, conduit, or metal housing. The line-to-neutral voltage of the source will cause current to flow in the hot conductor, through the arc path, and back through the ground path. The impedance of the conductor and the ground-return path (enclosure, conduit, or housing) depends on many factors. As a result, the fault-current value cannot be predicted. It can also increase or decrease as the fault condition continues.

It is apparent that many factors influence the magnitude, duration, and the effect of an arcing ground fault. Some conditions produce a large amount of fault current, while others limit the fault current to a relatively small amount. Damage to equipment that is caused by arc-current magnitude and the time that the arc persists can be very great. Probably the more important factor is the time period of the arcing voltage since the larger the arcing time, the more chance that the arc will spread to different areas within the equipment.

Ground-current relaying is one method used to protect equipment from ground faults. Current flow through a load or fault along the hot and neutral conductors and returns to the source on these conductors and, to some extent, along the ground path. The normal ground path current is very small. Therefore, essentially all the current flowing from the source is also returning on the same hot line and neutral conductor. However, if a ground fault occurs, the ground current will increase to the point where some current will escape through the fault and return via the ground path. As a result, the current returning on the hot and neutral conductors is less than the amount going out. The difference is an indication of the amount of current in the ground path. A relay, which senses this difference in currents, can act as a ground-fault protective device.

Ground-Fault Protection for Electric Motors

Motor protective systems offer protection in the 5- to 100-ampere range. This type of ground-fault protective system offers a protection against ground faults in both the single-phase and the three-phase systems. Many insulation system failures begin with a small leakage current which builds up with time until damage results. These ground-fault systems detect ground leakage currents while they are still small and, thus, prevent any extensive damage happening to the motors.

WIRING DESIGN CONSIDERATIONS FOR A DISTRIBUTION SYSTEM

The wiring design of electrical power distribution systems can be very complex. There are many factors which must be considered in the wiring design of a distribution system installed in a building. Wiring design standards are specified in the National Electrical Code (NEC) which is published by the National Fire Protection Association (NFPA). The NEC, local wiring standards, and electrical inspection policies should be considered in an electrical wiring design.

There are several distribution system wiring design considerations which are pointed out specifically in the NEC. We will deal with voltage-drop calculations, branch-circuit design, feeder-circuit design, and the design for grounding systems in this chapter.

The National Electrical Code (NEC)

The National Electrical Code sets forth the minimum standards for electrical wiring in the United States. The standards contained in the NEC are enforced by being incorporated into the different city, and community ordinances which deal with electrical wiring in residences, industrial plants, and commercial buildings. Therefore, these local ordinances conform to the standards set forth in the NEC.

In most areas of the United States, a license must be obtained by any individual who does electrical wiring. Usually a test administered by the city, county, or state must be passed in order to obtain this license. These tests are based on local ordinances and the NEC. The rules for electrical wiring that are established by the local electrical power company are also sometimes incorporated into the license test.

Electrical Inspections

When new buildings are constructed, they must be inspected to see if the electrical wiring meets the standards of the local ordinances, the NEC, and the local power company. The organization which supplies the electrical inspectors varies from one locality to another. Ordinarily, the local power company can advise individuals about whom to contact for information about electrical inspections.

Voltage Drop in Electrical Conductors

Although the resistance of electrical conductors is very low, a long length of wire could cause a substantial voltage drop. This is illustrated in Fig. 8-8. Remember that a voltage drop is current times resistance ($I \times R$). Therefore, whenever current flows through a system, a voltage drop is created. Ideally, the voltage drop caused by the resistance of a conductor will be very small.

However, a longer section of electrical conductor has a higher resistance. Therefore, it is sometimes necessary to limit the distance a conductor can extend from the power source to the load which it supplies. Many types of loads do not operate properly when a value less than the full source voltage is available.

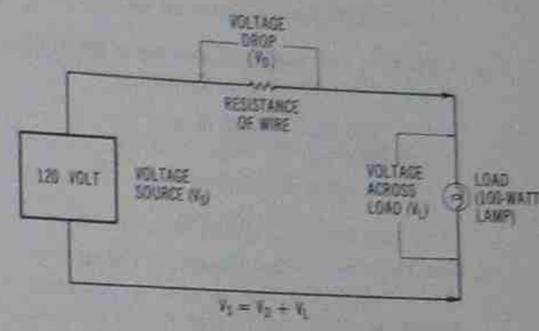


Fig. 8-8. Voltage drop in an electrical circuit.

You can also see from Fig. 8-8 that as the voltage drop (V_D) increases, the voltage applied to the load (V_L) decreases. As current in the system increases, V_D increases causing V_L to decrease since the source voltage stays the same.

Voltage-Drop Calculations Using Conductor Table

It is important when dealing with electrical wiring design to be able to determine the amount of voltage drop caused by conductor resistance. Table 6-3 is used to make these calculations. The National Electrical Code limits the amount of voltage drop that a system can have. This means that long runs of conductors must ordinarily be avoided. Remember that a conductor with a large cross-sectional area will cause a smaller voltage drop since its resistance is smaller.

To better understand how to determine the size of conductor required to limit the voltage drop in a system, we will look at a sample problem.

1. *Given*—A 200-ampere load located 400 feet (121.92 meters) from a 240-volt single-phase source. Limit the voltage drop to 2% of the source.
2. *Find*—The size of an RH copper conductor needed to limit the voltage drop of the system.
3. *Solution:*

a. The allowable voltage drop equals 240 volts times 0.02 (2%). This equals 4.8 volts.

b. Determine the maximum resistance for 800 feet (243.84 meters). This is the equivalent of 400 feet (121.92 meters) × 2, since there are two current-carrying conductors for a single-phase system.

$$R = \frac{V_D}{I}$$
$$= \frac{4.8\ V}{200\ A}$$
$$= 0.024 \text{ ohm, resistance for 800 feet.}$$

c. Determine the maximum resistance for 1000 feet (304.8 meters) of conductor.

$$\frac{800 \text{ feet}}{1000 \text{ feet}} = \frac{0.024 \text{ ohm}}{R}$$
$$800\,R = (1000)(0.024)$$
$$R = 0.030 \text{ ohm}$$

d. Use Table 6-3 to find the size of copper conductor which has the nearest dc resistance (ohms per 1000 feet) value that is equal to or less than the value calculated in 3c, above. The conductor chosen is conductor size 350 MCM, RH Copper.

e. Check this conductor with the proper ampacity table to assure that it is large enough to carry 200 amperes. Table 6-5 shows that a 350 MCM, RH copper conductor will handle 310 amperes of current; therefore, use 350 MCM conductors. (Always remember to use the largest conductor if Steps 3d and 3e produce conflicting values.)

Alternative Method of Voltage-Drop Calculation

In some cases, an easier method to determine the conductor size for limiting the voltage drop is to use one of the following formulas to find the cross-sectional (cmil) area of the conductor.

$$\text{cmil} = \frac{\rho \times I \times 2d}{V_D} \qquad \text{(Single-Phase Systems)}$$

or,

$$\text{cmil} = \frac{\rho \times I \times 1.73d}{V_D} \qquad \text{(Three-Phase Systems)}$$

where,

ρ is the resistivity from Table 6-2,
I is the load current in amperes,
V_D is the allowable voltage drop,
d is the distance from source to load in feet.

The sample problem given for a single-phase system in the preceding section could be set up as follows:

$$\text{cmil} = \frac{\rho \times I \times 2d}{V_D}$$
$$= \frac{10.4 \times 200 \times 2 \times 400}{240 \times 0.02}$$
$$= \frac{1{,}664{,}000}{4.8}$$
$$= 346{,}666$$
$$= 347 \text{ MCM.}$$

The next largest size is a 350 MCM conductor.

Branch-Circuit Design Considerations

A branch circuit is defined as a circuit which extends from the last overcurrent protective device of the power system. Branch circuits, according to the National Electrical Code, are either 15, 20, 30, 40, or 50 amperes in capacity. Loads larger than 50 amperes would not be connected to a branch circuit.

There are many rules in the National Electrical Code (NEC) which apply to branch-circuit design. The following information is based on the NEC. First, each circuit must be designed so that accidental short circuits or grounds do not cause damage to any part of the system. Then, fuses or circuit breakers are to be used as branch-circuit overcurrent protective devices. Should a short circuit or ground condition occur, the protective device should open and interrupt the flow of current in the branch circuit. One important NEC rule is that No. 16 or No. 18 (extension cord) wire may be tapped from No. 12 or No. 14 conductors but not larger than No. 12. This means that an extension cord of No. 16 wire should not be plugged into a receptacle which uses No. 10 wire. Damage to smaller wires (due to the heating effect) before the overcurrent device can open is eliminated by applying this rule. Lighting circuits are one of the most common types of branch circuits. They are usually either 15-ampere or 20-ampere circuits.

The maximum rating of an individual load (such as a portable appliance connected to a branch circuit) is 80% of the branch-circuit current rating. So, a 20-ampere circuit could not have a single load which draws more than 16 amperes. If the load is a permanently connected appliance, its current rating cannot be more than 50% of the branch-circuit capacity if portable appliances or lights are connected to the same circuit.

Voltage Drop in a Branch Circuit

Branch circuits must be designed so that sufficient voltage is supplied to all parts of the circuit. The distance that a branch circuit can extend from the voltage source or power distribution panel is, therefore, limited. A voltage drop of 3% is specified by the National Electrical Code as the maximum allowed for branch circuits in electrical wiring design.

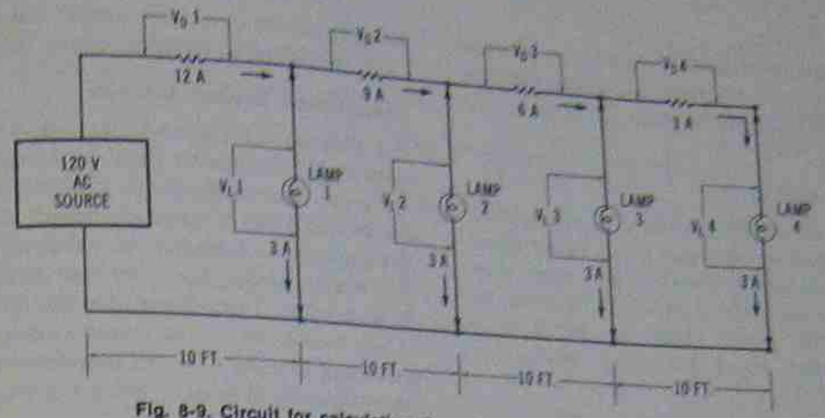


Fig. 8-9. Circuit for calculating the voltage drop in a branch circuit.

The method for calculating the voltage drop in a branch circuit is a step-by-step process which is illustrated by the following problem. Refer to the circuit diagram given in Fig. 8-9.

1. *Given*—A 120-volt 15-ampere branch circuit supplies a load which consists of four lamps. Each lamp draws 3 amperes of current from the source. The lamps are located at 10-foot (3.05-meter) intervals from the power distribution panel.
2. *Find*—The voltage across lamp No. 4.
3. *Solution:*

a. Find the resistance for 20 feet (6.1 meters) of conductor (same as 10-foot conductor × 2). A No. 14 copper wire is used for 15-ampere branch circuits. From Table 6-3, we find that the resistance of 1000 feet (304.8 meters) of No. 14 copper wire is 2.57 ohms. Therefore, the resistance of 20 feet of wire is:

$$\frac{20 \text{ feet}}{1000 \text{ feet}} = \frac{R}{2.57 \text{ ohm}}$$
$$1000\,R = (20)(2.57)$$
$$R = 0.0514 \text{ ohm.}$$

b. Calculate voltage drop V_D No. 1. (R equals the resistance of 20 feet of wire.)

$$V_D \text{ No. } 1 = I \times R$$
$$= 12\ A \times 0.0514\ \Omega$$
$$= 0.6168 \text{ V ac.}$$

Calculate load V_L No. 1. (The source voltage minus V_D No. 1.)

$$V_L \text{ No. } 1 = 120\ V - 0.6168\ V$$
$$= 119.383 \text{ volts.}$$

c. Calculate voltage drop and load No. 2.

$$V_D \text{ No. } 2 = I \times R$$
$$= 9\ A \times 0.0514\ \Omega$$
$$= 0.4626 \text{ V ac,}$$
$$V_L \text{ No. } 2 = 119.383\ V - 0.4626\ V$$
$$= 118.920 \text{ volts.}$$

d. Calculate voltage drop and load No. 3.

$$V_D \text{ No. } 3 = I \times R$$
$$= 6\ A \times 0.0514\ \Omega$$
$$= 0.3084 \text{ V ac,}$$
$$V_L \text{ No. } 3 = 118.920\ V - 0.3084\ V$$
$$= 118.612 \text{ volts.}$$

e. Calculate voltage drop and load No. 4.

$$V_D \text{ No. } 4 = I \times R$$
$$= 3\ A \times 0.0514\ \Omega$$
$$= 0.1542 \text{ V ac,}$$
$$V_L \text{ No. } 4 = 118.612\ V - 0.1542\ V$$
$$= 118.458 \text{ volts.}$$

Notice that the voltage across lamp No. 4 is substantially reduced from the 120-volt source value due to the voltage drop of the conductors. Also, notice that the resistances used to calculate the voltage drops represented both wires (hot and neutral) of the branch circuit. Ordinarily, 120-volt branch circuits do not extend more than 100 feet (30.48 meters) from the power distribution panel. The preferred distance is 75 feet (22.86 meters). The voltage drop in branch-circuit conductors can be reduced by making the circuit shorter in length or by using larger conductors.

In residential electrical wiring design, the voltage drop in many branch circuits is difficult to calculate since the lighting and portable appliance receptacles are placed on the same branch circuits. Since portable appliances and "plug-in" lights are not used all of the time, the voltage drop will vary according to the number of lights and appliances in use. This problem is

usually not encountered in an industrial or commercial wiring design for lights, since the lighting units are usually larger and are permanently installed on the branch circuits.

Branch-Circuit Wiring

A branch circuit usually consists of a nonmetallic-sheathed cable which is connected into a power distribution panel. Each branch circuit that is wired from the power distribution panel is protected by a fuse or circuit breaker. The power panel also has a main switch which controls all of the branch circuits that are connected to it.

Single-Phase Branch Circuits

A diagram of a single-phase three-wire (120/240-volt) power distribution panel is shown in Fig. 8-10. Notice that eight 120-volt branch circuits and one 240-volt circuit are available from the power panel. This type of system is used in most homes where several 120-volt branch circuits and, typically, three or four 240-volt branch circuits are required. Notice in Fig. 8-10 that each hot line has a circuit breaker while the neutral line connects directly to the branch circuits. Neutrals should never be opened (fused). This is a safety precaution in electrical wiring design.

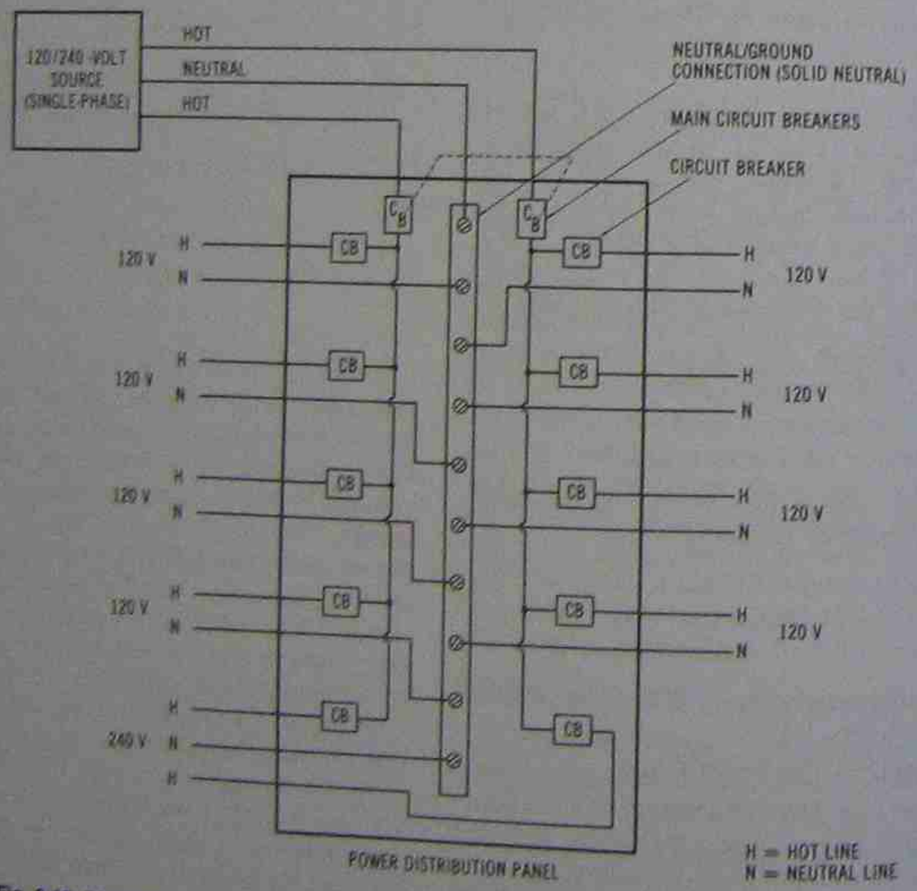


Fig. 8-10. Diagram of a power distribution panel for a single-phase three-wire branch circuit.

Three-Phase Branch Circuits

A diagram for a three-phase four-wire (120/208-volt) power distribution panel is shown in Fig. 8-11. There are three single-phase 120-volt branch circuits shown and two 208-volt three-phase branch circuits shown. The single-phase branches are balanced (one hot line from each branch). Each hot line has an individual circuit breaker. Three-phase lines should be connected so that an overload in the branch circuit will cause all three lines to open. This is accomplished by using a three-phase circuit breaker which is arranged internally as shown in Fig. 8-12.

Feeder-Circuit Design Considerations

Feeder circuits are used to distribute electrical power to power distribution panels. Many feeder circuits extend for very long distances; therefore, voltage drop must be considered in feeder-circuit design. In higher voltage feeder circuits, the voltage drop is reduced. However, many lower voltage feeder circuits require large-diameter conductors to provide a tolerable low

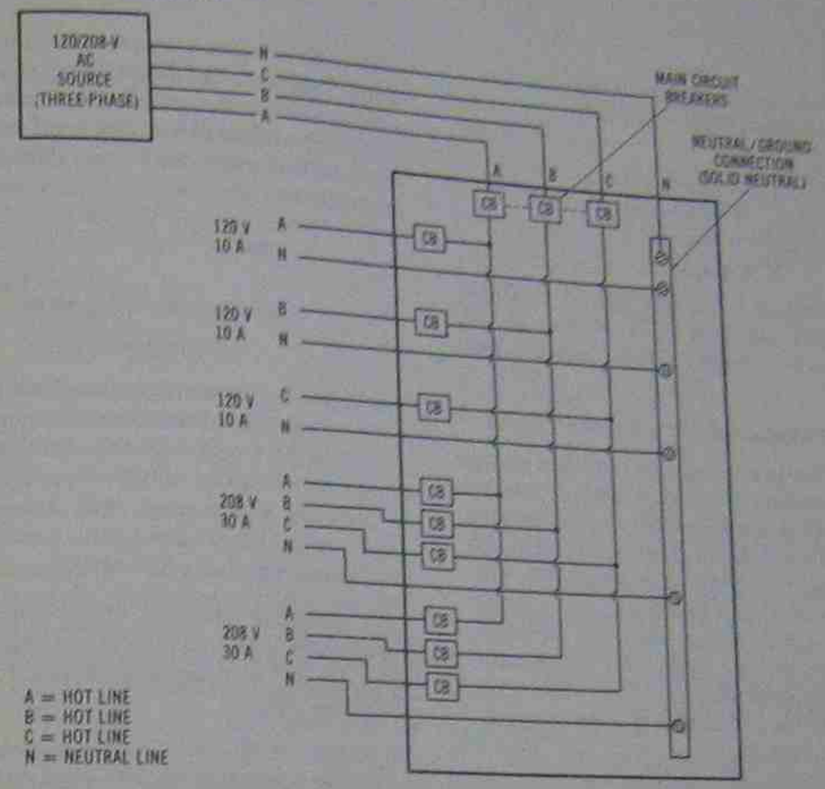


Fig. 8-11. Diagram of a power distribution panel for a three-phase four-wire branch circuit.

of voltage drop. High-current feeder circuits also present a problem in terms of the massive overload protection which is sometimes required. This protection is usually provided by system switchgear or load centers where the feeder circuits originate.

Determining the Size of Feeder Circuits

The amount of current which a feeder circuit must be designed to carry depends upon the actual load demanded by the branch-circuit power distribution panels which it supplies. Each power distribution panel will have a separate feeder circuit. Also, each feeder circuit must have its own overload protection.

The following problem is an example of size calculation for a feeder circuit.

1. *Given*—Three 15-kW fluorescent lighting units are connected to a three-phase four-wire (277/480-volt) system. The lighting units have a power factor of 0.8.
2. *Find*—The size of THW aluminum feeder conductors required to supply this load.

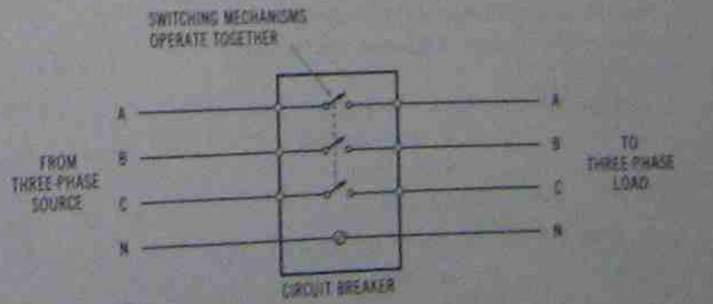


Fig. 8-12. Diagram of a three-phase circuit breaker.

3. *Solution:*

a. Find the line current:

$$I_L = \frac{P_T}{1.73 \times V_L \times pf}$$
$$= \frac{45{,}000 \text{ watts}}{1.73 \times 480 \text{ volts} \times 0.8}$$
$$= 67.74 \text{ Amps}$$

b. From Table 6-5, we find that the conductor size which will carry 67.74 amperes of current is a No. 3 AWG THW aluminum conductor.

Voltage Drop Calculation for a Feeder Circuit

Feeder-circuit design must take the conductor voltage drop into consideration. The voltage drop in a feeder circuit must be kept as low as possible so that maximum power can be delivered to the loads connected to the feeder system. The NEC allows a maximum 5% voltage drop in the combination of a branch and a feeder circuit; however, a 5% voltage reduction represents a significant power loss in a circuit. We can calculate power loss due to voltage drop as V^2/R, where V^2 is the voltage drop of the circuit and R is the resistance of the conductors of the circuit.

The calculation of feeder conductor size is similar to that for a branch-circuit voltage drop. The size of the conductors must be large enough to: (1) have the required ampacity, and (2) keep the voltage drop below a specified level. If the second requirement is not met, possibly due to a long feeder circuit, the conductors chosen must be larger than the ampacity rating requires.

The following problem illustrates the calculation of feeder conductor size based upon the voltage drop in a single-phase circuit.

1. *Given*—A single-phase 240-volt load in a factory is rated at 85 kilowatts. The feeders (two hot lines) will be 260-foot (79.25 meters) lengths of RHW copper conductor. The maximum conductor voltage drop allowed is 2%.
2. *Find*—The feeder conductor size required.
3. *Solution:*

a. Find the maximum voltage drop of the circuit.

$$V_D = \% \times \text{Load}$$
$$= 0.02 \times 240$$
$$= 4.8 \text{ volts}$$

b. Find the current drawn by the load.

$$I = \frac{\text{Power}}{\text{Voltage}}$$
$$= \frac{85{,}000}{240}$$
$$= 354.2 \text{ amperes}$$

c. Find the minimum circular-mil conductor area required. Use the formula for finding cmil in three-phase systems that was given in an earlier section.

$$\text{cmil} = \frac{\rho \times I \times 1.73\,d}{V_D}$$
$$= \frac{10.4 \times 72.25 \times 1.73 \times 300}{4.8}$$
$$= 81{,}245 \text{ cmil}$$

d. Determine the feeder conductor size. The closest and next larger conductor size in Table 6-3 is No. 1 AWG. Check Table 6-5 and you will see that a No. 1 AWG RH copper conductor will carry 130 amperes, much more than the required 72.25 amperes. Therefore, use No. 1 AWG RH copper conductors for the feeder circuit.

DETERMINING GROUNDING-CONDUCTOR SIZE

Grounding considerations in electrical wiring design were discussed previously. Another aspect in wiring design is to determine the size of the grounding conductor required in a circuit. All circuits which operate at 150 volts or less must be grounded; therefore, all residential electrical systems must be grounded. Higher voltage systems used in industrial and commercial buildings have grounding requirements that are specified by the NEC and by local codes. A ground at the service entrance of a building is usually a metal water pipe which extends uninterrupted underground or a grounding electrode that is driven into the ground near the service entrance.

The size of the grounding conductor is determined by the current rating of the system. Table 8-2 lists equipment grounding-conductor sizes for interior wiring while Table 8-3 lists the minimum grounding-conductor sizes for system grounding of service entrances. The sizes of grounding conductors listed in Table 8-2 are for equipment grounds which connect to raceways, enclosures, and metal frames for safety purposes. Note that a No. 12 or a No. 14 wiring cable, such as 12-2 WG NMC can have a No. 18 equipment ground. The ground is contained in the same cable sheathing as the hot conductors. Table 8-3 is used to find the minimum size of grounding conductors needed for service entrances, based upon the size of the hot line conductors used with the system.

Table 8-2. Equipment Grounding-Conductor Sizes for Interior Wiring

Ampere Rating of Distribution Panel	Grounding Conductor Size (AWG)*	
	Copper	Aluminum
15	14	12
20	12	10
30	10	8
40	10	8
60	10	8
100	8	6
200	6	4
400	3	1
600	1	00
800	0	000
1000	00	0000

* No. 12 or No. 14 wiring cable can use a No. 18 equipment ground.

Table 8-3. System Grounding-Conductor Sizes for Service Entrances

Conductor Size (Hot Line)		Grounding Conductor Size	
Copper	Aluminum	Copper (AWG)	Aluminum (AWG)
No. 2 AWG or smaller	No. 0 AWG or smaller	8	6
No. 1 or 0 AWG	No. 00 or 000 AWG	6	4
No. 00 or 000 AWG	No. 0000 AWG or 250 MCM	4	2
No. 000 AWG to 350 MCM	250 MCM to 500 MCM	2	0
350 MCM to 600 MCM	500 MCM to 900 MCM	0	000
600 MCM to 1100 MCM	900 MCM to 1750 MCM	00	0000

PARTS OF INTERIOR ELECTRICAL WIRING SYSTEMS

Some parts of interior electrical distribution systems have been discussed previously. Such types of equipment as transformers, switchgear, conductors, insulators, and protective equipment are parts of interior wiring systems. There are, however, certain parts of interior electrical distribution systems which are unique to the wiring system itself. These parts include the nonmetallic-sheathed cables (NMC), the metal-clad cables, the rigid conduit, and the electrical metallic tubing (EMT).

Nonmetallic-Sheathed Cable (NMC)

Nonmetallic-sheathed cable is a common type of electrical cable used for interior wiring. NMC, sometimes referred to as *Romex* cable, is used in residential wiring systems almost exclusively. The most common type used is No. 12-2 WG, which is illustrated in Fig. 8-13. This type of NMC comes in 250-foot rolls for

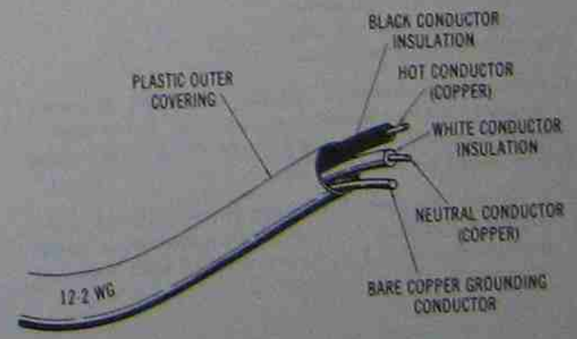


Fig. 8-13. Nonmetallic-sheathed cable.

interior wiring. The cable has a thin plastic outer covering with three conductors inside. The conductors have colored insulation which designates whether the conductor should be used as a hot, neutral, or equipment ground wire. For instance, the conductor connected to the hot side of the system has black or red insulation, while the neutral conductor has white or gray insulation. The equipment grounding conductor has either a green insulation or no insulation (bare conductor). There are several different sizes of bushings and connectors used for the installation of NMC in buildings.

The designation No. 12-2 WG means that (1) the copper conductors used are No. 12 AWG as measured by an American Wire Gage (AWG), (2) there are two current-carrying conductors, and (3) the cable comes with a ground (WG) wire. A No. 14-3 WG cable, in comparison, would have three No. 14 conductors and a grounding conductor. NMC ranges in size from No. 14 to No. 1 AWG copper conductors and from No. 12 to No. 2 AWG aluminum conductors.

Metal-Clad Cable

Metal-clad cable is similar to NMC except that it has a flexible spiral metal covering rather than a plastic covering. A common type of metal-clad cable is called *BX cable*. Like NMC, BX cable contains two or three conductors. There are also several sizes of connectors and bushings used in the installation of BX cable. The primary advantage of this type of metal-clad cable is that it is contained in a metal enclosure that is flexible so that it can be bent easily. Other metal enclosures are usually more difficult to bend.

Rigid Conduit

The exterior of rigid conduit looks like water pipe. It is used in special locations for enclosing electrical conductors. Rigid conduit comes in 10-foot lengths which must be threaded for joining the pieces together. The conduit is secured to metal wiring boxes by locknuts and bushings. It is bulky to handle and takes a long time to install.

Electrical Metallic Tubing (EMT)

EMT or thinwall conduit is somewhat like rigid conduit except that it can be bent with a special conduit-bending tool. EMT is easier to install than rigid conduit since no threading is required. It also comes in 10-foot lengths. EMT is installed by using compression couplings to connect the conduit to metal wiring boxes. Interior electrical wiring systems use EMT extensively since it can be easily bent, can be connected together, and can be connected to metal wiring boxes.

PROBLEMS

1. Find the proper size of THW copper conductor needed to limit to 2% the voltage drop of a 400-ampere load that is connected 150 feet from a 480-volt single-phase source. Use Table 6-3 to find the conductor size.

2. Three 20,000-watt loads are connected to a three-phase wye-connected system. The power factor of the system is 0.9. Find the minimum size of RH copper feeder conductors needed to supply this load.

3. Determine the branch-circuit rating and size of conductors needed for the following systems:
   a. 2500 watt, 240-volt heater.
   b. 1800-watt, 120-volt washer.
   c. 12,000-watt, 240-volt range.
   d. 800-watt, 120-volt toaster.

4. Calculate the maximum distance a 120-volt 20-ampere branch circuit can extend from the power source when a 3-kW appliance is connected to the circuit. The voltage drop should be limited to 2%.

5. A 120-volt 20-ampere branch circuit (using No. 12 copper conductors) extends 150 feet. Loads connected at 30-foot intervals each draw 3.5 amperes. With all loads connected, calculate the voltage at the last outlet.

6. Calculate the longest distance a single-phase 20-ampere 120-volt branch circuit can extend from the power source. Use No. 12 AWG copper conductors and limit the voltage drop to 2%.

7. A single-phase 120-volt load is rated at 40 kilowatts. The feeder circuit will be 400 feet of RH copper conductors. Find the minimum conductor size necessary to supply this load and still limit the voltage drop to 1%.

8. A 240-volt three-phase delta system converts 30 kW of power per phase (balanced). The system power factor is unity (1.0). The feeders will be 400 feet of RHW copper conductor. Find the minimum conductor size necessary to limit the voltage drop to 2%.

9. Find the minimum size of copper grounding conductor needed for the following situations:
   a. No. 10 AWG copper service entrance.
   b. 250 MCM aluminum service entrance.
   c. 200-ampere service entrance.
   d. 500 MCM copper service entrance.
   e. 600-ampere service entrance.

UNIT III

Power Control Systems

In this unit, electrical power control systems are studied. The fundamentals of electrical power control are discussed in Chapter 9. This chapter examines several of the fundamental devices and types of equipment which are used for electrical power control. This equipment includes such basic devices as contactors, relays, switches, and the newer equipment, such as electronic control devices.

Chapter 10 examines the mechanical and electronic control systems that are in use today with electrical machinery. The motor control systems that are used extensively in day-to-day business are also discussed in this chapter.

Fig. 3. The Electrical Power System

CHAPTER 9

Power Control Devices

The control of electrical power is a very important part of the electrical power system operation of today. Control is the most complex part of the electrical systems. It is, therefore, necessary to limit the discussion in this chapter primarily to some of the common types of electromechanical equipment and devices which are used for electrical power control. Control equipment and devices are used in conjunction with many types of electrical loads. Since electrical motors (mechanical loads) use about 50% of all electrical power, we will concentrate mainly on electrical motor-control equipment and devices. In most cases, similar equipment and devices are used to control electrical lighting and heating loads.

POWER CONTROL STANDARDS, SYMBOLS, AND DEFINITIONS

There is a great amount of fundamental knowledge that is needed in order to fully understand electrical power control. Individuals who are concerned with electrical power control systems should have a good knowledge of the standards, symbols, and definitions which govern electrical power control.

NEMA Standards

The National Electrical Manufacturers' Association (NEMA) has developed standards for electrical control systems. NEMA standards are used extensively to obtain information about the construction and performance of various electrical power control equipment. These standards provide information concerning the voltage, frequency, power, and current ratings for various equipments.

ANSI and IEEE Standards

There are two well-known organizations which publish standards that are of importance to industry. These organizations are the American National Standards Institute (ANSI) and the Institude of Electrical and Electronic Engineers (IEEE). The standards published by these organizations are for the use of the manufacturing industries as well as consumers and, in some cases, the general public. These standards are subject to review periodically; therefore, industrial users should keep up-to-date by obtaining the revisions.

These standards were developed through input from manufacturers, consumers, government agencies, and scientific, technical, and professional organizations. Often these published standards are used by industry as well as governmental agencies. It should be noted that the National Electrical Code discussed previously is an American National Standards Institute standard.

Definitions

There are several basic definitions which are used when dealing with electrical power control. These definitions are particularly important when interpreting control diagrams and standards. A listing of several of the important power control definitions follows. You should study these definitions.

Across-the-line control—A method of motor starting in which a motor is connected directly across the power lines when it is started.

Automatic starter—A self-acting starter which is completely controlled by control switches or some other sensing mechanism.

Auxiliary contact—A contact that is part of a switching system. It is in addition to the main contacts and is operated by the main contacts.

Braking—A control method that is used to rapidly stop and hold a motor.

Circuit breaker—An automatic device that opens under abnormally high-current conditions and can be manually or automatically reset.

Contact—A current-conducting part of a control device which is used to open or close a circuit.

Contactor—A control device that is used to repeatedly open or close an electric power circuit.

Controller—A device or group of devices that systematically control the delivery of electric power to the load or loads connected to it.

Disconnect—A control device or group of devices that will open so that electrical current in a circuit will be interrupted.

Drum controller—Sets of electrical contacts that are mounted on the surface of a rotating cylinder; usually for controlling the on-off forward-reverse condition of a load.

Electronic control—Usually solid-state devices or gas-filled tubes which perform part of the control function of a system.

Full voltage control—A control system that connects equipment directly across the power lines when it is started.

Fuse—A circuit-protection device that disconnects a circuit when an overcurrent condition occurs. However, it is self-destructive and must be replaced.

Horsepower—The power output or mechanical work rating of an electrical motor.

Jogging—Momentary operation which causes a small movement of the load that is being controlled.

Magnetic contactor—A contactor which is operated electromagnetically and usually controlled by push buttons activated by an operator.

Manual controller—An electric control device that functions when operated by mechanical means, usually by an operator.

Master switch—A switch that controls the power delivered to other parts of a system.

Motor—A device (mechanical load) for converting electrical power to mechanical power in the form of rotary motion.

Multispeed starter—An electrical power-control device which provides for varying the speed of a motor.

Overload relay—Overcurrent protection for a load. While it is in operation, it maintains the interruption of the load from the power supply until it is reset or replaced.

Overload relay reset—A push button that is used to reset a thermal overload relay after the relay has been overloaded.

Pilot device—A control device which directs the operation of another device or devices.

Plugging—A braking method which causes a motor to develop a retarding force in the reverse direction.

Push button—A button-type control switch which is manually operated for actuating or disconnecting some load device.

Push-button station—A housing for the push buttons that are used to control equipment.

Reduced-voltage starter—A control device that applies a reduced voltage to a motor when it is started.

Relay—A control device that is operated by one electrical circuit to control a load which is part of another electrical circuit.

Remote control—A system in which the control of an electrical load takes place from some distant location.

Safety switch—An enclosed manually operated disconnecting switch used to turn a load off when necessary.

Solenoid—An electromagnetically actuated control device that is used to produce linear motion for performing various control functions.

Starter—An electric controller that is used to start, stop, and protect the motor which is connected to it.

Timer—A control device that provides variable time periods so that a control function may be performed.

Symbols

One should have an understanding of the electrical symbols which are commonly used with power control systems. A few of these are somewhat different from basic electrical symbols. Some typical symbols are shown in Fig. 9-1. You should especially observe the symbols that are used for the various types of switches and push buttons.

POWER CONTROL USING SWITCHES

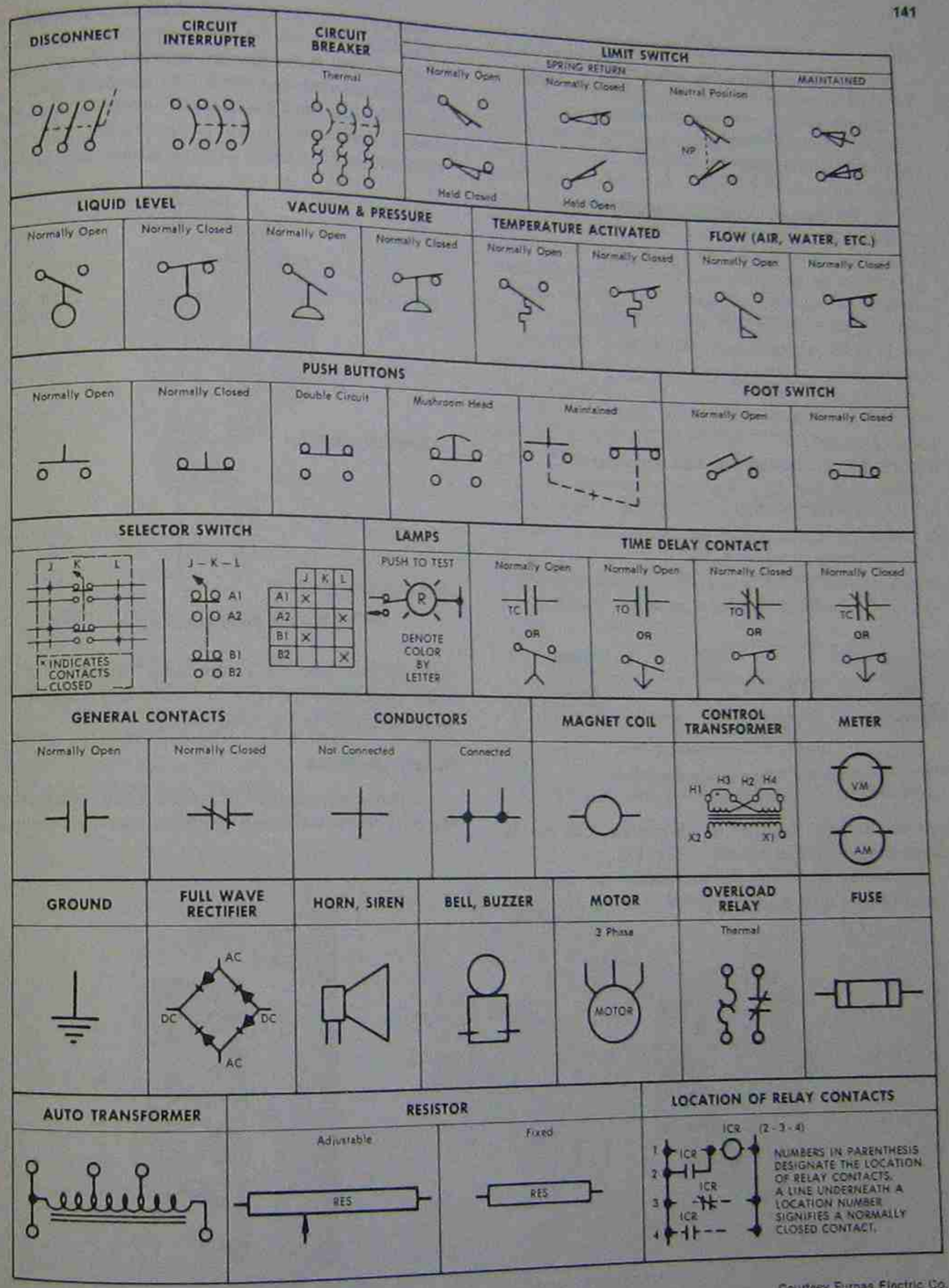
An important, but often overlooked, part of electrical power control is the various types of switches used. This section will examine the many types of switches that are used to control electrical power. The primary function of a switch is to turn a circuit on or off; however, many more complex switching functions can be performed using switches. The emphasis in this section will be on switches that are used for motor control. Keep in mind that other load devices can also be controlled in a similar manner by switches.

Toggle Switches

Among the simplest types of switches are toggle switches. The symbols for several kinds of toggle switches are shown in Fig. 9-2, while Fig. 9-3 shows one type of toggle switch. You should become familiar with the symbols that are used for various types of toggle switches and with the control functions that they can accomplish.

Push-Button Switches

Push-button switches are commonly used. Many motor-control applications use push buttons as a means of starting, stopping, or reversing a motor; the push buttons are manually operated to close or open the control circuit of the motor. There are several types of push buttons used in the control of motors. Fig. 9-4 diagrams some push-button styles. Push but-



Courtesy Furnas Electric Co.

Fig. 9-1. Common power control symbols.

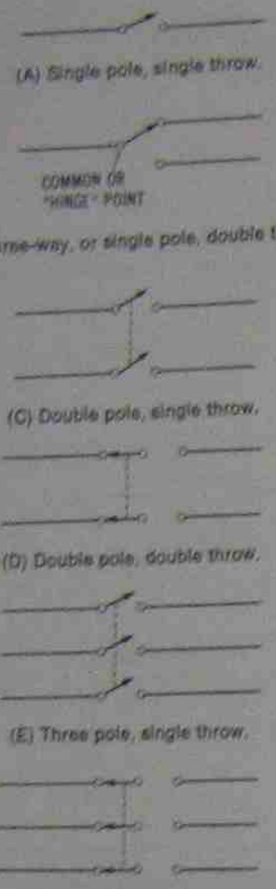
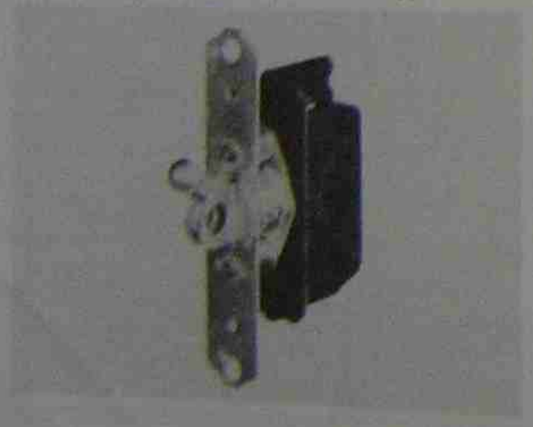


Fig. 9-2. Types of toggle switches.

tons are usually mounted in enclosures such as the motor control station shown in Fig. 9-5.

Ordinarily, push buttons are either the normally closed (N.C.) or normally open (N.O.) type. However,



Courtesy Cutler-Hammer

Fig. 9-3. A 2-pole, open-type, momentary contact, lockable switch.

there are a few modifications of these as shown by the symbols of Fig. 9-1. A normally closed push button is closed until it is depressed manually. It will open a circuit when it is depressed. The normally open push button is open until it is manually depressed and, then once it is depressed, it will close a circuit. The "start" push button of a motor control station is a normally

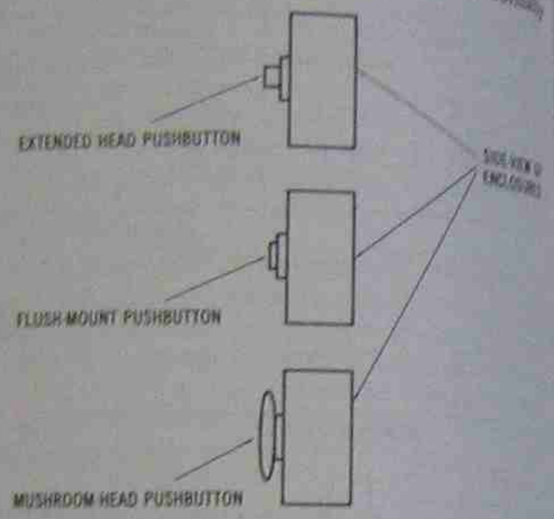
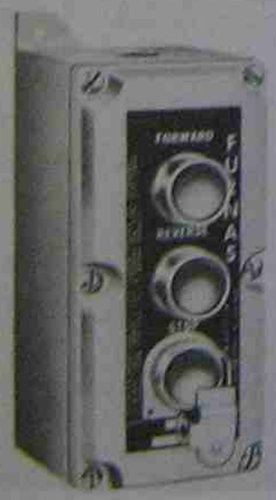


Fig. 9-4. Push-button styles.

open (N.O.) type while the "stop" switch is a normally closed (N.C.) type. A "start-stop" push-button switch is shown in Fig. 9-6.

Rotary Switches

Another common type of switch is the rotary switch. Many different switching combinations can be wired



Courtesy Furnas Electric Co.

Fig. 9-5. Push-button switching unit.

by using a rotary switch. The shaft of a rotary switch is attached to sets of moving contacts. These moving contacts touch different sets of stationary contacts which are mounted on ceramic segments when the rotary shaft is turned to different positions. The shaft

Courtesy Cutler-Hammer

Fig. 9-6. A "start-stop" push-button switch.

can lock into place in any of several positions. A common type of rotary switch is shown in Fig. 9-7. Rotary switches are usually controlled by manually turning the rotary shaft clockwise or counterclockwise. A knob is normally fastened to the end of the rotary shaft to permit easier turning of the shaft.

Limit Switches

Some typical limit switches are shown in Fig. 9-8. They are made in a variety of sizes. Limit switches are merely on/off switches which use a mechanical movement to cause a change in the operation of the electrical control circuit of a motor or other load device. The electrical current developed as a result of the mechanical movement is used to *limit* movement of the machine or to make some change in its operational sequence. Limit switches are often used in sequencing, routing, sorting, or counting operations in industry. Ordinarily, they are used in conjunction with hydraulic or pneumatic controls, electrical relays, or other motor-operated machinery such as drill presses, lathes, or conveyor systems.

In its most basic form, a limit switch converts mechanical motion into an electrical control current. Some parts of the limit switch are labeled on Fig. 9-8. Notice that the *cam* is an external part which is usually mounted on a machine. The cam applies force to the actuator of the limit switch. The *actuator* is the part of the limit switch which causes the internal N.O. or N.C. contacts to change state. The actuator operates due to either linear or rotary motion of the cam which ap-

Courtesy Cutler-Hammer

Fig. 9-8. A subminiature snap-acting switch with actuator.

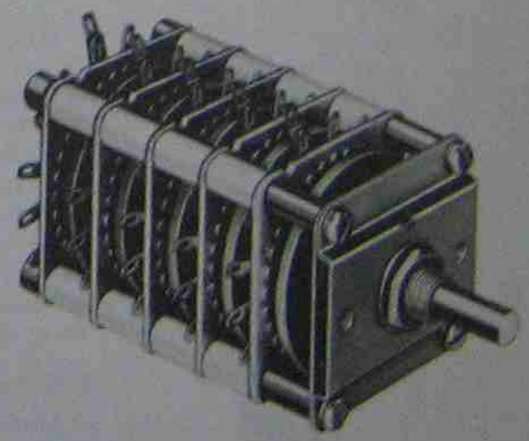


Fig. 9-7. A rotary switch.

Courtesy Cutler-Hammer

plies force to the limit switch. Two other terms associated with limit switches are pretravel and overtravel. *Pretravel* is the distance that the actuator must move to change the normally open or normally closed state of the limit-switch contacts. *Overtravel* is the distance the actuator moves beyond the point where the contacts change state. Both pretravel and overtravel settings are important in machine setups where limit switches are used.

Temperature Switches

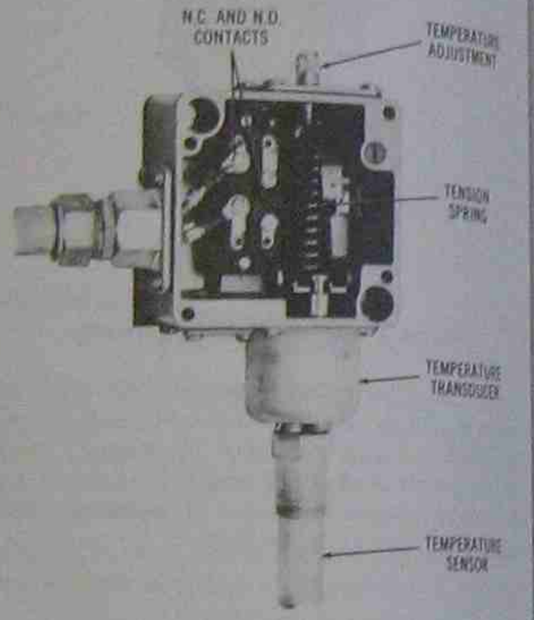
Temperature switches are among the most common types of control devices used in industry. A temperature switch is shown in Figs. 9-9 and 9-10. The control element of a temperature switch contains a specific amount of liquid. The liquid increases in volume when the temperature increases. Thus, changes in temperature can be used to change the position of a set of contacts within the temperature-switch enclosure. Temperature switches may be adjusted throughout a range of temperature settings.

Courtesy Square D Co.

Fig. 9-9. A temperature switch (exterior view).

Float Switches

Float switches are used when it is necessary to control the level of a liquid. The float switch shown in Fig. 9-11 has its operating lever connected to a rod and float assembly. The float assembly is placed into a tank of liquid where the motion of the liquid controls the movement of the operating lever of the float switch. The float switch usually has a set of normally open and normally closed contacts which are controlled by the position of the operating lever. The contacts are connected to a pump-motor circuit. In operation, the normally open contacts would be connected in series with



Courtesy Square D Co.

Fig. 9-10. A temperature switch (interior view).

a pump-motor control circuit. When the liquid level is reduced, the float switch would be lowered to a point where the operating lever would be moved far enough that the contacts would be caused to change to a closed state. The closing of the contacts would cause the pump motor to turn on. More liquid would, then, be pumped into the tank until the liquid level had risen high enough to cause the float switch to turn the pump motor off.

Pressure Switches

Another type of electrical control device is called a pressure switch. A pressure switch has a set of electrical contacts which change states due to a variation in the pressure of air, hydraulic fluid, water, or some other medium. Some pressure switches are diaphragm

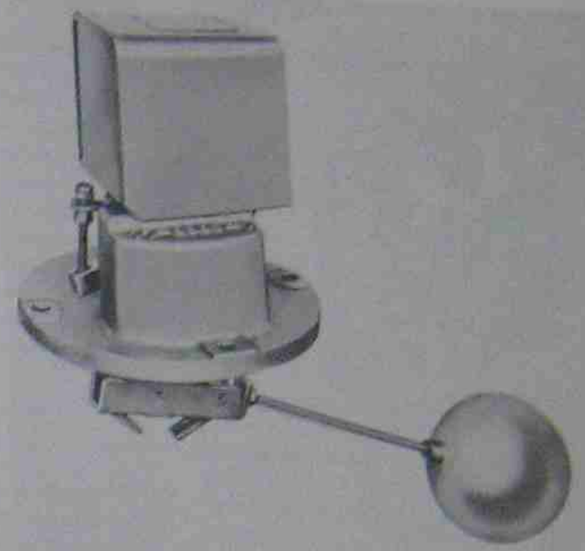


Fig. 9-11. A float switch.

Courtesy Modular Control Co.

operated. They rely upon the intake or expelling of a medium, such as air, which takes place in a diaphragm assembly within the pressure-switch enclosure. Another type of pressure switch uses a piston mechanism to initiate the action of opening or closing the switch contacts. In this type, the movement of a piston is controlled by the pressure of the medium (air, water, etc.). External and internal views of a pressure switch are shown in Figs 9-12 and 9-13.

Foot Switches

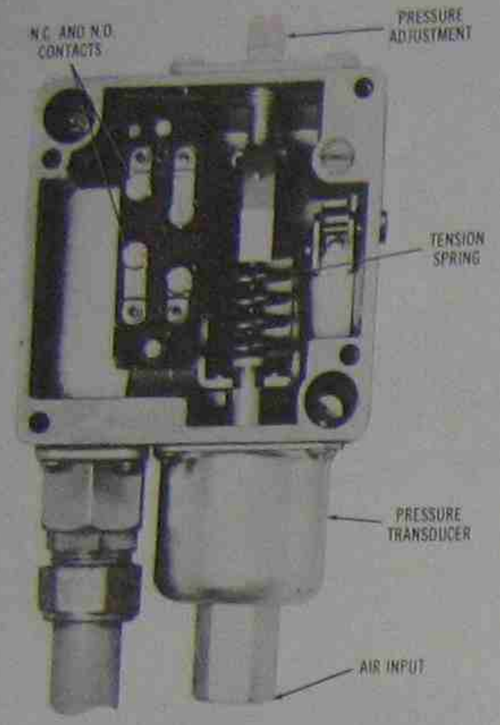
A foot switch is a switch that is controlled by a foot pedal. This type of switch is used for applications where a machine operator has to use both hands during the operation of the machine. The foot switch provides an additional control position for the operation of a machine for such time as when the hands cannot be used.

Drum-Controller Switches

Drum controllers are special-purpose switches which are ordinarily used to control large motors. They may be used with either single-phase or three-phase motors. The usual functions of a drum-controller switch are for start/stop control or for the forward/reverse/stop control of electrical motors. A drum-controller switch is illustrated in Fig. 9-14. Notice the high-current contacts which are moved as the handle of the controller is turned.

Courtesy Square D Co.

Fig. 9-12. A pressure switch (external view).



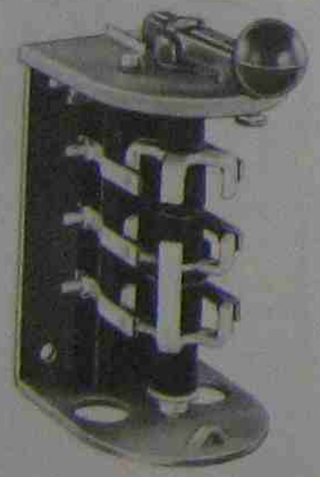
Courtesy Square D Co.

Fig. 9-13. A pressure switch (internal view).

Pilot Lights for Switches

Pilot lights usually operate in conjunction with switches. Motor-control devices often require that some visual indication of the operating condition of the motor be provided. Pilot lights of various types are used to provide such a visual indication. They usually indicate either an *on* or *off* condition. For instance, a pilot light could be wired in parallel with a motor to indicate when it is on. Some types of pilot lights are:

1. Full-voltage across-the-line lights—These are the less expensive lights but they do not last as long.
2. Transformer-operated lights—These use a lower voltage to activate the lamp, but they require the expense of an additional transformer which ordinarily reduces the operating voltage to 6 volts.
3. Resistor-type lights—This light uses a series resistor to reduce the voltage across the lamp.
4. Illuminated push button—The functions of the push button and the pilot-light device are combined into one item of equipment which reduces the mounting-space requirement.



Courtesy Furnas Electric Co.

Fig. 9-14. A drum-controller switch.

CONTROL EQUIPMENT FOR ELECTRIC MOTORS

There are several types of electromechanical equipment used for the control of electric-motor power. The selection of power-control equipment will affect the efficiency of the power-system operation and the performance of the machinery. It is very important to use the proper type of equipment for each power-control application. This section will concentrate on the types of equipment used for motor control.

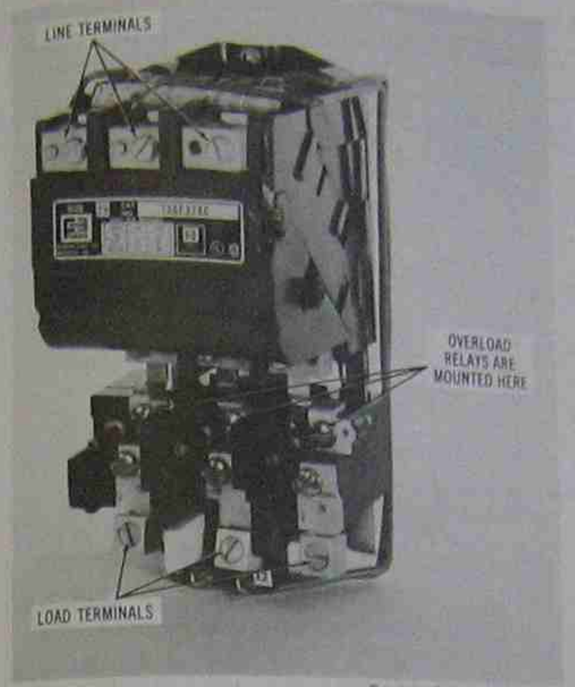
Motor-Starting Control

A motor-starting device is a type of power control when used to accelerate a motor from a "stopped" condition to its normal operating speed. There are many variations in motor-starter design, the simplest being a manually operated on/off switch connected in series with one or more power lines. This type of starter is used only for smaller motors which do not draw an excessive amount of current.

Another type of motor starter is the magnetic starter which relies upon an electromagnetic effect to open or close the power-source circuit of the motor. This type of starter is shown in Fig. 9-15. Often, motor starters are grouped together for the control of adjacent equipment in an industrial plant. Such groupings of motor starters and associated control equipment, shown in Fig. 9-16, are called motor control centers. Control centers provide an easier access to the power distribution system since they are more compact and the control equipment is not scattered throughout a large area. Motor-starting systems will be discussed in greater detail in Chapter 10.

Functions of Motor Starters

Various types of motor starters are used for control of motor power. The functions of a starter vary in com-



Courtesy Furnas Electric Co.

Fig. 9-15. A magnetic starter.

plexity; however, motor starters usually perform one or more of the following functions:

1. On and off control.
2. Acceleration.
3. Overload protection.
4. Reversing direction of rotation.

Courtesy Klockner-Moeller Corp.

Fig. 9-16. Motor control center.

Some starters control a motor by being connected directly across the power input lines. Other starters reduce the level of input voltage that is applied to the motor when it is started so as to reduce the value of the starting current. Ordinarily, motor overload protection is contained in the same enclosure as the magnetic contactor.

Sizes of Motor Contactors

The contactors used with motor starters are rated according to their current capacity. The National Electrical Manufacturers Association (NEMA) has developed standard sizes for magnetic contactors according to their current capacity. Table 9-1 lists the NEMA standard sizes for magnetic contactors. By looking at this chart, you can see that a NEMA size 1 contactor has a 30-ampere current capacity if it is open (not mounted in a metal enclosure) and a 27-ampere capacity if it is enclosed. The corresponding maximum horsepower ratings of loads for each of the NEMA contactor sizes are also shown in Table 9-1.

Manual Starters

Some motors use manual starters to control their operation. Fig. 9-17 shows a manual starter that is used to control a motor. This type of starter provides starting, stopping, and overload protection similar to that of a magnetic contactor. However, manual starters must be mounted near the motor that is being controlled. Remote-control operation is not possible as it would be with a magnetic contactor. This is due to the small control current that is required by the magnetic contactor. Magnetic contactors also provide a low-voltage protection by the drop-out of the contacts when a low-voltage level occurs. Manual starters remain closed until they are manually turned off. They are usually limited to small sizes.

Motor Overload Protection

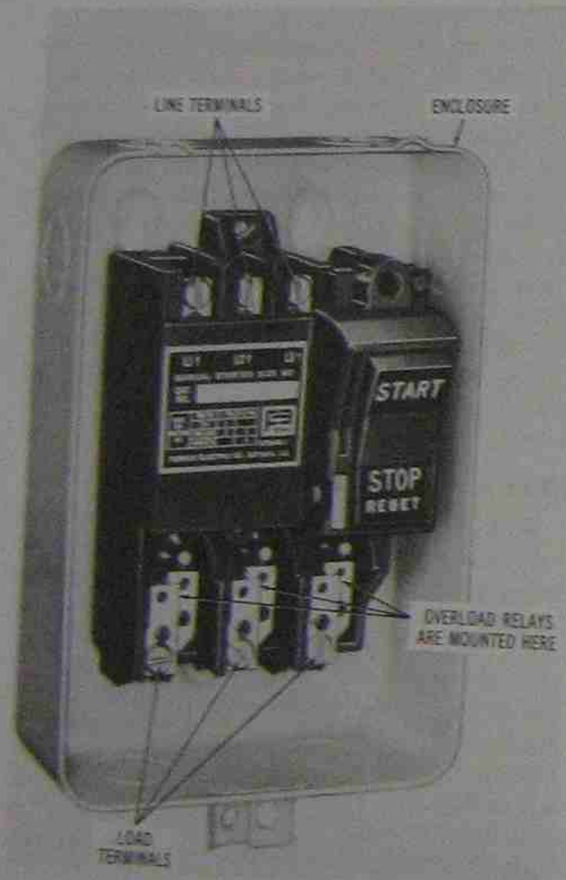
Both manual and magnetic starters can have overload protection contained in their enclosures. It is common practice to place either bimetallic or melting-alloy overload relays in series with the motor branch-circuit power lines. These devices are commonly called heaters. They were discussed in Chapter 7. An overload protective relay is selected according to the current rating of the motor circuit to which it is connected. An identification number is used on overload protective devices. This number is used to determine the current that will cause the overload device to "trip" or open the branch circuit. Some typical overload protection or heater tables are given in Tables 9-2 and 9-3.

Table 9-2 is used for melting-alloy–type devices. The Table Number (26142) is selected according to the

Table 9-1. Sizes of Magnetic Contactors

NEMA Size	Ampere Rating		Maximum Horsepower Rating of Load					
			Single-Phase		Three-Phase			
	Open	Enclosed	115 V	230 V	115 V	200 V	230 V	460 V
00	10	9	0.33	1	0.75	1.5	1.5	2
0	20	18	1	2	2	3	3	5
1	30	27	2	3	3	7.5	7.5	10
2	50	45	3	7.5	7.5	10	15	25
3	100	90	7.5	15	15	25	30	50
4	150	135	—	—	25	40	50	100
5	300	270	—	—	—	75	100	200
6	600	540	—	—	—	150	200	400
7	900	810	—	—	—	—	300	600
8	1350	1215	—	—	—	—	450	900
9	2500	2250	—	—	—	—	800	1600

type and size of controller, the size of motor, and the type of power distribution (single-phase or three-phase). For example, a heater with an H37 code number is used with a motor that has a full-load current of 18.6 to 21.1 amperes.



Courtesy Furnas Electric Co.

Fig. 9-17. A manual starter.

Table 9-2. Melting-Alloy Devices

Table 26142					
Full Load Motor Amps.	Heater Code	Full Load Motor Amps.	Heater Code	Full Load Motor Amps.	Heater Code
12.6 - 14.5	H33	21.2 - 22.2	H38	34.6 - 38.9	H43
14.6 - 16.0	H34	22.3 - 23.6	H39	39.0 - 44.7	H44
16.1 - 16.9	H35	23.7 - 26.2	H40	44.8 - 48.8	H45
17.0 - 18.5	H36	26.3 - 30.1	H41	48.9 - 54.2	H46
18.6 - 21.1	H37	30.2 - 34.5	H42	54.3 - 60.0	H49

Courtesy Furnas Electric Co.

Table 9-3 is used with bimetallic overload relays. They are selected in the same manner as melting-alloy relays. However, this table shows the trip amperes of the heater. A heater with a K53 code number has a 13.9 trip-ampere rating. Thus, a current in excess of

Table 9-3. Bimetallic Devices

Table 62K					
Trip Amperes	Heater Code	Trip Amperes	Heater Code	Trip Amperes	Heater Code
1.95	K21	5.59	K36	17.0	K56
2.12	K22	6.39	K37	18.3	K57
2.31	K23	6.88	K39	19.8	K58
2.49	K24	7.78	K41	21.0	K60
2.75	K26	8.42	K42	22.5	K61
3.05	K27	9.54	K43	24.1	K62
3.29	K28	10.1	K49	25.7	K63
3.69	K29	11.5	K50	28.3	K64
4.01	K31	12.6	K52	31.1	K67
4.32	K32	13.9	K53	34.6	K68
4.77	K33	15.1	K54		
5.14	K34	16.0	K55		

Courtesy Furnas Electric Co.

13.9 amperes would cause the heater element to trip. This would open the motor branch circuit by removing the power from the motor.

Classes of Motor Starters

The types of motor starters which are commercially available are divided into five classes. These classes, which were established by the National Electrical Manufacturers Association (NEMA), are:

1. *Class A*—Alternating-current, manual or magnetic, air-break or oil-immersed starters which operate on 600 volts or less.
2. *Class B*—Direct-current, manual or magnetic, air-break starters which operate on 600 volts or less.
3. *Class C*—Alternating-current, intermediate voltage starters.
4. *Class D*—Direct-current, intermediate voltage starters.
5. *Class E*—Alternating-current, magnetic starters which operate on 2200 volts to 4600 volts. Class E1 uses contacts and Class E2 uses fuses.

Sizes of Manual Starters

A uniform method has also been established for sizing manual motor starters. Some examples of the sizes of full-voltage manual starters are:

1. Size M-O—For single-phase 115-volt motors up to 1 horsepower.
2. Size M-1—For single-phase 115-volt motors up to 2 horsepower.
3. Size M-1P—For single-phase 115-volt motors up to 3 horsepower.

These sizes are summarized in Table 9-4.

Table 9-4. Sizes of Manual Starters

Starter Size	Maximum Horsepower Rating of Load				Ampere Rating
	Single-Phase		Three-Phase		
	115 V	230 V	200-230 V	460-575 V	
M-0	1	2	3	5	20
M-1	2	3	7.5	10	30
M-1P	3	5	—	—	30

Combination Starters

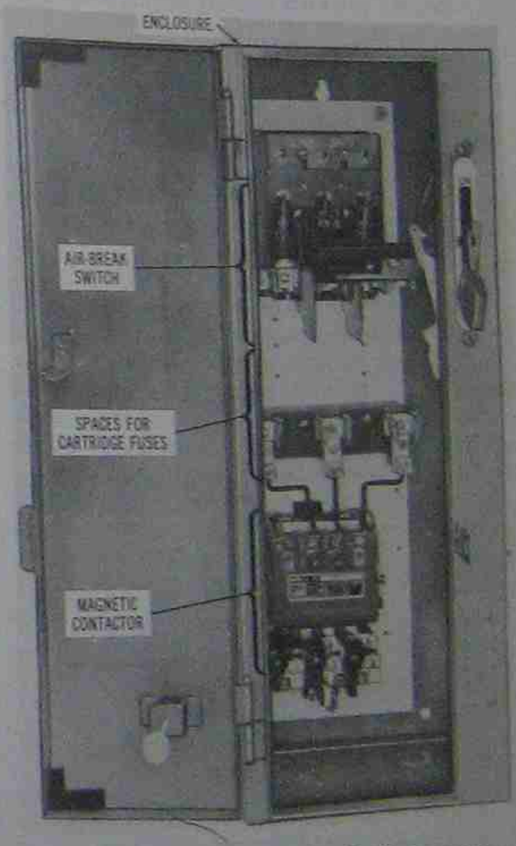
A popular type of motor starter used in control applications is the combination starter. These starters are made with protective devices such as fused-disconnect switches, air-type circuit breakers, or a system of fuses and circuit breakers mounted in a common enclosure. They are used on systems of 600 volts or less. A combination magnetic starter is shown in Fig. 9-18.

Criteria for Selecting Motor Controllers

There are several important criteria which should be considered when selecting electric motor controllers. Among these are:

1. The type of motor—Ac or dc, induction or wound rotor.
2. The motor ratings—Voltage, current, duty cycle, and service factor.
3. Motor operating conditions—Ambient temperature and type of atmosphere.
4. Utility company regulations—Power factor, demand factor, load requirements, and the local codes.
5. Type of mechanical load connected to motor—Torque requirement.

In order to become more familiar with the criteria listed above, you must be able to interpret the data on a motor nameplate. The information contained on a typical nameplate is summarized as follows:



Courtesy Furnas Electric Co.

Fig. 9-18. A combination magnetic starter.

Manufacturing Co.—The company that built the motor.
Motor Type—A specific type of motor; i.e., split-phase ac, universal, three-phase induction, etc.
Identification Number—Number assigned by the manufacturer.
Model Number—Number assigned by the manufacturer.
Frame Type—Frame size defined by NEMA.
Number of Phases (ac)—Single-phase or three-phase.
Horsepower—The amount produced at rated speed.
Cycles (ac)—Frequency the motor should be used with (usually 60 Hz).
Speed (r/min)—The amount at rated hp, voltage, and frequency.
Voltage Rating—Operating voltage of motor.
Current Rating (Amperes)—Current drawn at rated load, voltage, and frequency.
Thermal Protection—Indicates the type of overload protection used.
Temperature Rating (°C)—Amount of temperature that the motor will rise over ambient temperature, when operated.
Time Rating—Time the motor can be operated without overheating (usually continuous).
Amps—Current drawn at rated load, voltage, and frequency.

Chapter 14 deals further with the characteristics of electric motors.

Motor-Controller Enclosures

The purpose of a motor-controller enclosure is obvious. The operator is protected against accidental contact with high voltages which could cause death or shock. In some cases, however, the enclosures are used to protect the control equipment from its operating environment, which may contain water, heavy dust, or combustible materials. The categories of motor-controller enclosures were standardized by the National Electrical Manufacturers Association (NEMA). The following list, courtesy of Furnas Electric Company, summarizes various classifications.

NEMA 1 General-Purpose enclosures protect personnel from accidental electrical contact with the enclosed apparatus. These enclosures satisfy indoor applications in normal atmospheres which are free of excessive moisture, dust, and explosive materials.

NEMA 3 (3R) Weatherproof enclosures protect the control from weather hazards. These enclosures are suitable for applications on ship docks, canal locks, and construction work, and for application in subways and tunnels. The door seals with a rubber gasket. They are furnished with conduit hub and pole mounting bracket.

NEMA 4 Weathertight enclosures are suitable for application outdoors on ship docks and in dairies, breweries, etc. This type meets standard hose test requirements. They are sealed with a rubber gasket in the door.

NEMA 4X Corrosion Resistant fiberglass enclosures are virtually maintenance free. These U.L. listed units are adaptable to any conduit system by using readily available metal, fiberglass or PVC conduit hubs and are suitable for NEMA 3, 3R, 3S, 4 and 12 applications because they are dust-tight, rain-tight, water-tight, and oil-tight.

NEMA 12 Industrial-Use enclosure also satisfies dust-tight applications. These enclosures exclude dust, lint, fibers, and oil or coolant seepage. The hinged cover seals with a rubber gasket.

NEMA 13 Oil-tight push-button enclosures protect against dust, seepage, external condensation, oil, water, and coolant spray.

NEMA 7. For atmospheres containing hazardous gas, NEMA 7 enclosures satisfy Class 1, Group C or D applications as outlined in Section 500 of the "National Electric Code Standard of the National Board of Fire Underwriters for Electrical Wiring and Apparatus." These cast aluminum enclosures are for use in atmospheres containing ethylether vapors, ethylene, cyclopropane, gasoline, hexane, naptha, benzine, butane, propane, alcohol, acetone, benzol, lacquer solvent vapors or natural gas. Machined surfaces between the cover and the base provide the seal.

NEMA 9. For atmospheres containing explosive dust, NEMA 9 enclosures satisfy Class II, Group E, F, and G applications as outlined by the National Electrical Code for metal dust, carbon black, coal, coke, flour, starch, or grain dusts. Enclosure is cast aluminum with machined surfaces between cover and base to provide seal.

NEMA TYPES 1B1, 1B2, 1B3 Flush Types provide behind the panel mounting into machine bases, columns, or plaster walls to conserve space and to provide a more pleasant appearance. NEMA 1B1 mounts into an enclosed machine cavity. NEMA 1B2 includes its own enclosure behind the panel to exclude shavings and chips which might fall from above. NEMA 1B3 for plaster walls includes an adjustment to compensate for wall irregularities.

OTHER ELECTROMECHANICAL POWER CONTROL EQUIPMENT

There are so many types of electromechanical power control equipment used today that it is almost impossible to discuss each type. However, some of the very important types will be discussed in the following paragraphs.

Relays

Relays represent one of the most widely used control devices available today. The electromagnet of a relay contains a stationary core. Mounted close to one end of the core is a movable piece of magnetic material called the *armature*. When the coil is activated electrically, it produces a magnetic field in the metal core. The armature is then attracted to the core, which in turn produces a mechanical motion. When the coil is de-energized, the armature is returned to its original position by spring action.

The armature of a relay is generally designed so that electrical contact points respond to its movement. Activation of the relay coil will cause the contact points to "make" or "break" according to the design of the relay. A relay could be described as an electromagnetic switching mechanism. There are an almost endless number of special-purpose relays and switch combinations used for electrical power control. Fig. 9-19 shows a typical assortment of relays, while Fig. 9-20 shows a simplified diagram of the construction of a relay that is used to control a motor.

Relays use a small amount of current to create an electromagnetic field that is strong enough to attract the armature. When the armature is attracted, it either opens or closes the contacts. The contacts, then, either turn on or turn off circuits that are using large amounts of current. The minimal current that must flow through the relay coil in order to create a magnetic field strong enough to "attract" the armature is known as the "pickup" or "make" current. The current through the relay coil that allows the magnetic field to become weak enough to release the armature is known as the "break" or "dropout" current.

There are two types of contacts used in conjunction with most relays—normally open (N.O.) and normally closed (N.C.). The normally open contacts remain *open* when the relay coil is de-energized and closed only when the relay is energized. The normally closed contacts remain *closed* when the relay is de-energized and open only when the coil is energized.

Solenoids

A solenoid, shown in Fig. 9-21, is an electromagnetic coil with a movable core that is constructed of a magnetic material. The core, or plunger, is sometimes attached to an external spring. This spring causes the plunger to remain in a fixed position until moved by the electromagnetic field that is created by current through the coil. This external spring also causes the core or plunger to return to its original position when the coil is de-energized.

Solenoids are used for a variety of control applications. Many gas and fuel-oil furnaces use solenoid valves to automatically turn the fuel supply on or off upon demand. Most dishwashers use one or more solenoids to control the flow of water.

Specialized Relays

There are many types of relays used for electrical power control. *General-purpose relays* are used for low-power applications. They are relatively inexpensive and small in size. Many small general-purpose relays are mounted in octal base (8-pin) plug-in sockets. *Latching relays* are another type of relay. They are almost identical to the relays discussed previously, but they have a latching mechanism which holds the contacts in position after the power has been removed from the coil. A latching relay usually has a special type of unlatching coil connected in series with a push-button stop switch. *Solid-state relays* are used where improved reliability or a rapid rate of operation are necessary. Electromagnetic relays will wear out after prolonged use and have to be replaced periodically. Solid-state relays, as do other solid-state devices, have a long life expectancy. They are not sensitive to shock, vibration, dust, moisture, or corrosion. *Timing relays* are used to turn a load device on or off after a specific period of time. One popular type is a pneumatic timing relay such as the one shown in Fig. 9-22. The operation of a pneumatic timing relay is dependent upon the movement of air within a chamber. Air movement is controlled by an adjustable orifice that controls the rate of air movement through the chamber. The air-flow rate determines the rate of movement of a diaphragm or piston assembly. This assembly is connected to the contacts of the relay. Therefore, the orifice adjustment controls the air-flow rate, which determines the time from the activation of the relay until a load connected to it is turned on or off. There are other types of timing

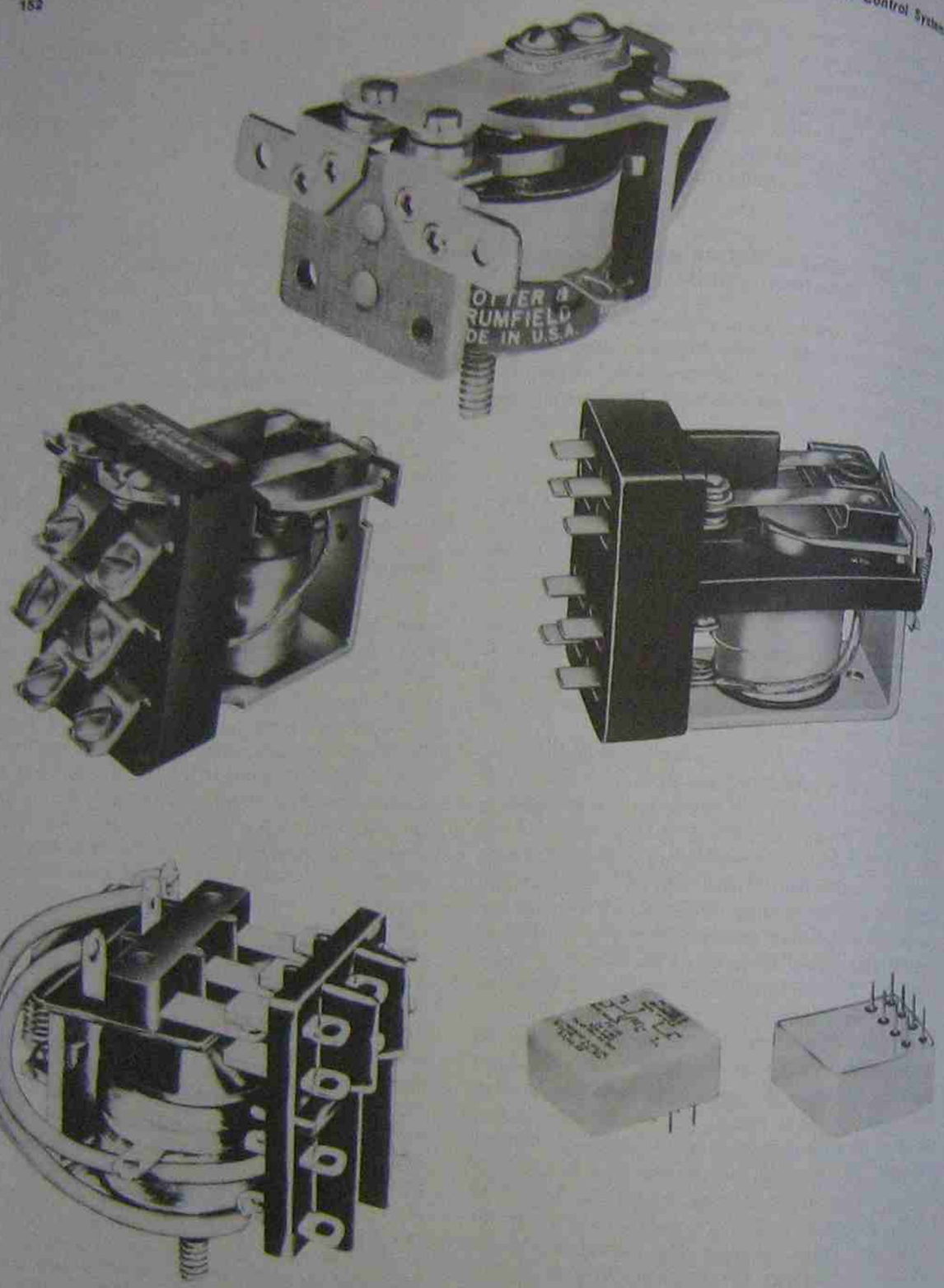


Fig. 9-19. A typical assortment of relays.

Courtesy Potter & Brumfield Div., AMF, Inc.

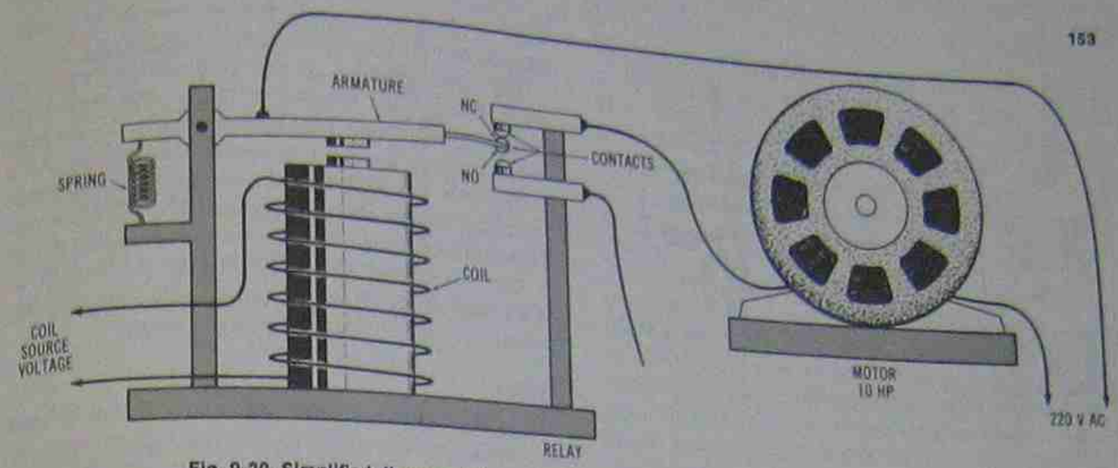


Fig. 9-20. Simplified diagram of the construction of a relay that is used to control a motor.

relays, such as solid-state, thermal, oil-filled, dashpot, and motor-driven timers. Timing relays are useful for sequencing operations where a time delay is required between operations. A typical application would be as follows: (1) a "start" push button is pressed; (2) a timing relay is activated; (3) after a 5-second time delay, a motor is turned on.

ELECTRONIC POWER CONTROL

Several books have been written about electronic power control. However, it is necessary to limit our discussion to some of the most common devices which are used for electrical power control. Among these devices are the thyratron tube, silicon-controlled rectifiers (SCRs), and triacs.

Thyratrons

A thyratron is a very common power control tube. This device is often called a grid-controlled rectifier because of the unusual type of control that the grid element of the tube has upon its conduction. Thyratrons are classified as gaseous or vapor tubes, which indicate a high current-conduction capability. Fig. 9-23 shows the internal structure and schematic symbol of a thyratron. A thyratron is a gas-filled diode tube with a grid structure. The grid in this case is used to control the ionizing condition of the gas within the enclosure. The structure of this electrode is unique. All of the current must pass through a single hole or aperture located between the cathode and the anode. A strong negative voltage applied to this element easily delays

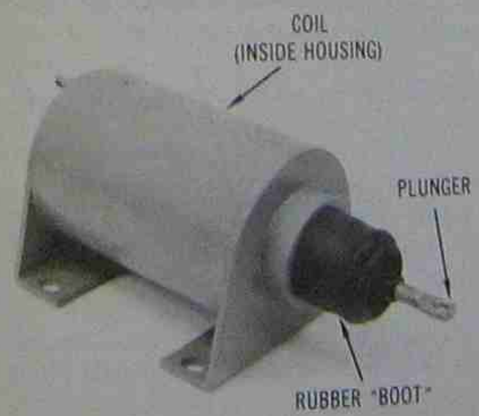
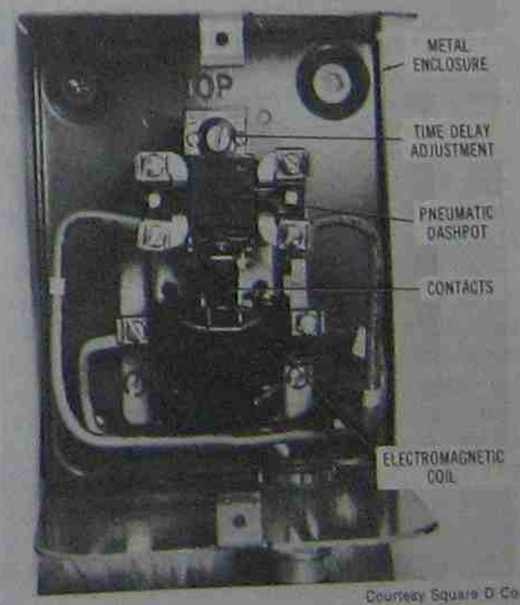


Fig. 9-21. A solenoid.



Courtesy Square D Co.

Fig. 9-22. Pneumatic timing relay.

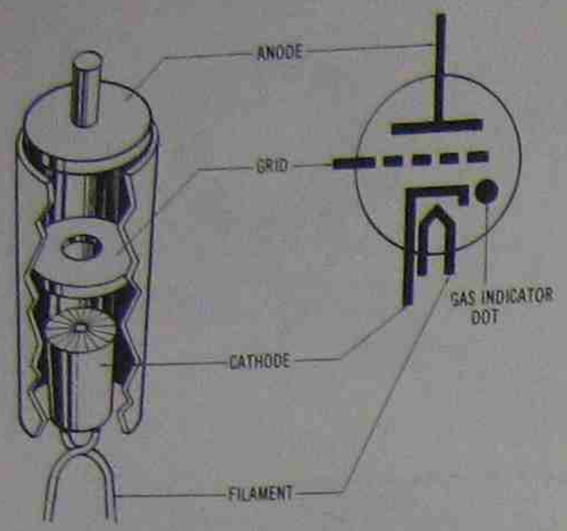


Fig. 9-23. Internal structure and schematic symbol of a thyratron tube.

the starting time of conduction. After conduction occurs, the grid loses its control and the thyratron operates as a diode. The grid, therefore, is used only to *delay* the starting time of conduction. The thyratron works very well as a speed-control device for direct-current or universal motors.

Silicon-Controlled Rectifiers

Conduction time control can also be achieved by using a silicon-controlled rectifier, or SCR. This device is the solid-state equivalent of the thyratron. It has the advantage of being rugged in construction, self-contained in a small package, does not require a heating source, provides instant-on control, and can respond to frequencies of 50 kHz or more. The SCR is very rapidly replacing the thyratron in practically all applications today. Fig. 9-24 shows the junction diagram, schematic symbol, element names, and voltage-current characteristic curve of an SCR.

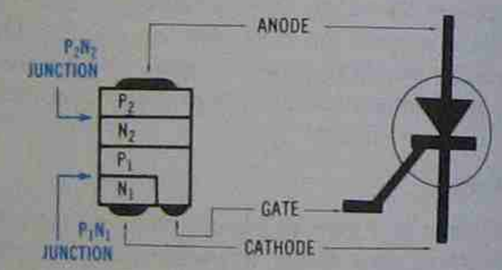
The voltage-current characteristic curve illustrated in Fig. 9-24B shows that an SCR has two conducting states to consider in its operation. Quadrant I shows the forward conduction region of operation. This characteristic shows how the SCR will go into conduction when the forward breakover voltage (V_{BO}) is exceeded. When conduction occurs, the internal resistance of the device drops to a rather low value like that of most diodes. The total current passing between the cathode and anode must, therefore, be limited by an external resistor. This resistance may be supplied by the device being controlled or by a separate load resistor. A small change in gate current can, then, be used to effectively control a large amount of anode-cathode current passing through the SCR.

The third quadrant of the characteristic curve of the SCR shows the location of the reverse breakdown conduction condition. This point is similar to the peak reverse voltage (prv) of a conventional diode. As a general rule, the SCR will be permanently damaged if operating voltages exceed this value. The prv represents the maximum voltage that can be applied to the device in the reverse-bias direction. Today, prv ratings of SCRs range from 25 to 2000 volts. SCRs are very important devices for electrical power control.

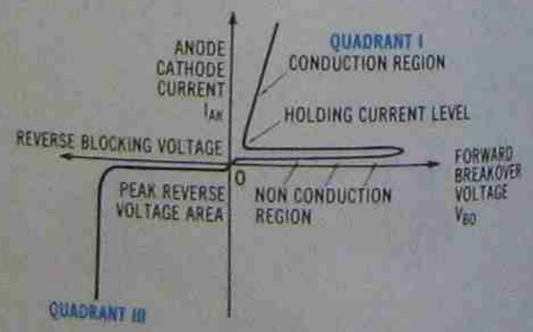
Triacs

The triac is a unique control device. It can be used for producing a variable ac voltage output. Also, ac power control can be accomplished very effectively and accurately with a single triac control circuit. Fig. 9-25 shows a junction diagram, schematic symbol, and voltage-current conduction characteristic curve of a triac. Notice that the junction diagram of this device forms an $N_1P_1N_2P_2$ junction structure between Main No. 1 and Main No. 2 while the gate is connected to the N_1P_1 junction near Main No. 1. From Main No. 2 to Main No. 1, the triac also forms an $N_3P_2N_2P_1$ juncture structure with the gate connected near Main No. 1 and using N_4 and P_1.

When ac is applied to a triac, Main No. 2 will be positive and Main No. 1 will be negative for a half

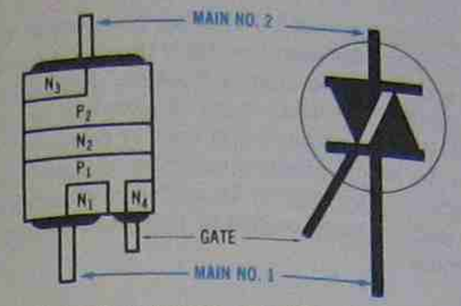


(A) Junction structure and schematic symbol.

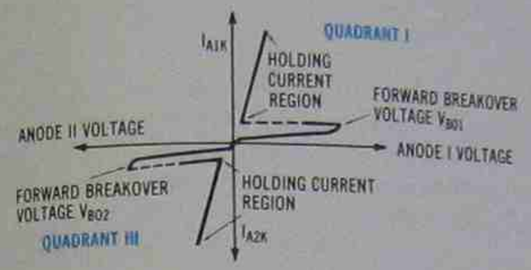


(B) Characteristic curve.

Fig. 9-24. Diagram of an SCR.



(A) Junction diagram and schematic symbol.



(B) Characteristic curve.

Fig. 9-25. Diagram of a triac.

cycle or the positive alternation of the applied ac. This voltage will cause the triac to operate in Quadrant I of the I-V characteristic curve of Fig. 9-25B. With no gate current applied, V_{BO1} will be quite large and will not turn on unless an extremely large value of V_{AK} is reached.

When gate current is applied to a triac, V_{BO1} is *reduced* to a lower value, which causes it to go into conduction. Either a positive or a negative gate voltage can be used to achieve this biasing condition. Quadrant I of the I-V characteristic curve shows this condition of operation. As a result, current will flow into Main No. 1, the P_1 material, and on into the N_2P_2 region, which is forward biased by Main No. 2. Conduction current through this device will be sustained when it moves into the holding-current region of the I-V characteristic curve.

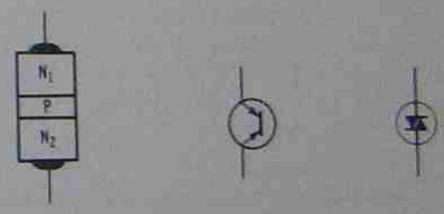
During the negative alternation of an applied sine wave, Main No. 2 of the triac will become negative, and Main No. 1 will be positive. Quadrant III of the I-V characteristic curve of the triac is used to display this condition of operation. With no gate current applied as indicated, V_{BO2} will be quite large and no conduction will occur unless an extremely high-valued V_{AK} is reached.

When gate current is applied to the triac, V_{BO2} can be reduced to a lesser value which will cause it to go into easy conduction. Either a positive or a negative voltage can be used to forward bias the gate junction of this device. When biasing occurs, conduction current will flow from Main No. 2 through the forward-biased N_3P_2 junction and, then, into the N_2P_1 junction. The N_2P_1 junction will, then, see a significant increase in current from the gate junction. This current added to that of the N_3P_2 junction lowers V_{BO2} and causes complete conduction to occur. The resulting characteristic is a mirror image of the conduction characteristic of Quadrant I.

In normal operation, the circuit of a triac must be designed so that it only goes into conduction by action of the gate. The applied source voltage must, therefore, be of a value that is somewhat less than that normally needed to overcome the operating V_{BO}. This characteristic, therefore, becomes a critical factor when selecting a triac to do a specific control function. Transient voltages must also be limited in order to avoid uncontrolled triggering of a triac. Diacs are often used in triac circuits to limit these voltage spikes to amplitude levels that will not damage or trigger the gate junction.

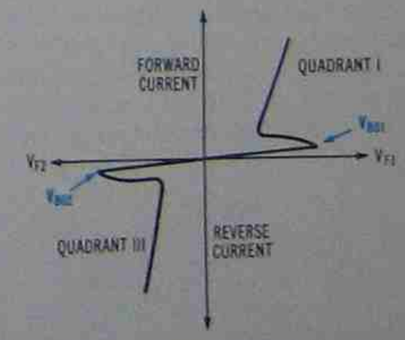
Diacs

A *diac*, shown in Fig. 9-26, is basically a bidirectional diode that can be triggered into conduction with voltage. The crystal structures of N_1 and N_2 are identical in nearly all respects so that the two junctions will have matched operating characteristics. A diac, therefore, goes into conduction at precisely the same positive or negative voltage level. A device of this type is "triggered" into conduction by reaching a specific voltage



(A) Crystal structure.

(B) Symbols.



(C) Voltage-current characteristic curve.

Fig. 9-26. Diagram of a diac.

value. For voltage values less than the trigger level, the device is nonconducting.

After the breakover voltage of a diac has been reached, current conduction will occur very quickly. A resistor placed in series with the device will limit the conduction current to a safe operating level in either direction. The voltage across a diac will also decrease quite readily as it increases in conduction. This conduction is known as the *negative resistance* of the diac. The pronounced curve that takes place after V_{bo} is reached shows this characteristic in Quadrants I and III.

In addition to the limiting function, diacs are often used as trigger devices. In this application, a diac is used to start the conduction of another device. As a result of this action, precise conduction time control can be applied to an ac signal. Triac-diac combinations are often used for speed control of dc motors and universal motors.

CHAPTER 10

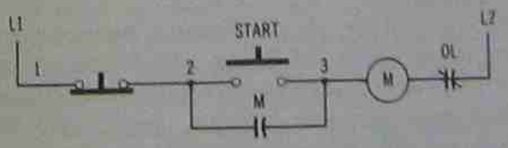
Operational Control Systems

Chapter 9 dealt with the equipment and devices which are commonly used for electrical power control. Now, the operational power control systems will be discussed in this chapter. Some specific applications of the equipment and devices that were studied in Chapter 9 will be investigated in this chapter.

BASIC CONTROL SYSTEMS

Electrical power control systems are used with many types of loads. The most common electrical loads are motors, so our discussion will deal mainly with electric motor control. However, many of the basic control systems are also used to control lighting and heating loads. Generally, the controls for lighting and heating loads are less complex.

Several power control circuits are summarized in Figs. 10-1 through 10-9. Fig. 10-1 is a start-stop push-button control circuit with overload protection (OL). Notice that the "start" push button is normally open

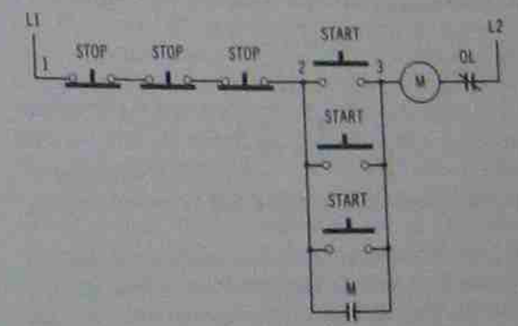


Courtesy Furnas Electric Co.

Fig. 10-1. A start-stop push-button control circuit with overload protection.

(N.O.) and the "stop" push button is normally closed (N.C.). Single-phase lines L1 and L2 are connected across the control circuit. When the start push button is pushed, a momentary contact is made between points 2 and 3. This causes the N.O. contact (M) to close. A complete circuit between L1 and L2 results that causes the electromagnetic coil (M) to be energized. When the normally closed stop push button is pressed, the circuit between L1 and L2 will open. This causes contact M to open and turn the circuit off.

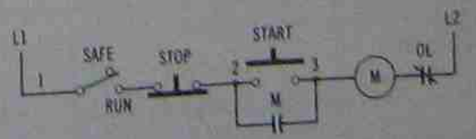
The circuit B in Fig. 10-2 is the same type of control as the circuit given in Fig. 10-1. In the circuit of Fig. 10-2, the start-stop control of a load can be accomplished from three separate locations. Notice that the start push buttons are connected in parallel and the stop push buttons are connected in series. The control of one load from as many locations as is desired can be accomplished with this type of control circuit.



Courtesy Furnas Electric Co.

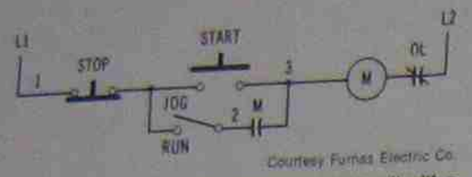
Fig. 10-2. A start-stop control circuit with low-voltage protection and control from three locations.

The next circuit (Fig. 10-3) is the same as the circuit in Fig. 10-1 except that a "safe-run" switch is provided. The "safe" position assures that the start push button will not activate the load. A "start-safe" switch circuit often contains a key which the machine operator uses to turn the control circuit on or off.



Courtesy Furnas Electric Co.

Fig. 10-3. A start-stop control circuit with a safe-run selector switch.



Courtesy Furnas Electric Co.

Fig. 10-4. A start-stop push-button control circuit with a jog-run selector switch.

Fig. 10-4 is also like the circuit of Fig. 10-1 but with a "jog-run" switch added in series with the normally open contact (M). In the "run" position, the circuit would operate just like the circuit of Fig. 10-1. The "jog" position is used so that a complete circuit between L1 and L2 will be achieved and sustained only while the start push button is pressed. With the selector switch in the "jog" position, a motor can be rotated a small amount, at a time, for positioning purposes. *Jogging* or *inching* is defined as the momentary operation of a motor to provide small movements of its shaft.

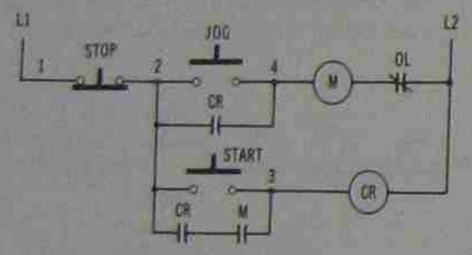


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Fig. 10-5. A push-button control circuit for start-stop-jogging.

Fig. 10-5 shows a circuit that is another method of motor-jogging control. This circuit has a separate push button for jogging which relies upon a normally open contact (CR) to operate. Two control relays are used with this circuit.

The circuit in Fig. 10-6 is a forward-reverse push-button control circuit with both forward and reverse limit switches (normally closed switches). When the "forward" push button is pressed, the load will operate until the "forward" limit switch is actuated. The load

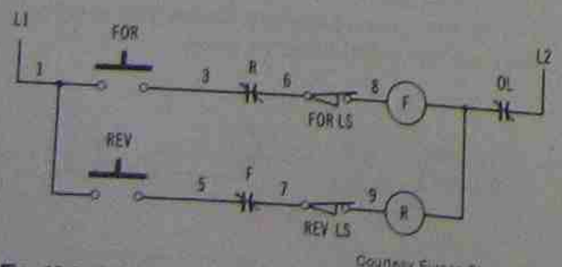

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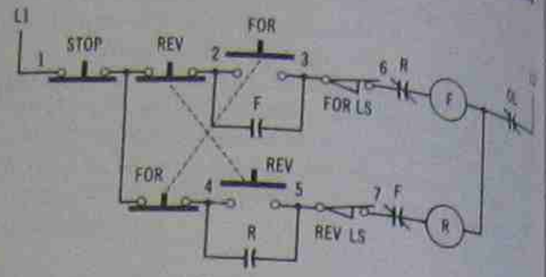
Fig. 10-6. A forward-reverse push-button control circuit with forward and reverse limit switches.



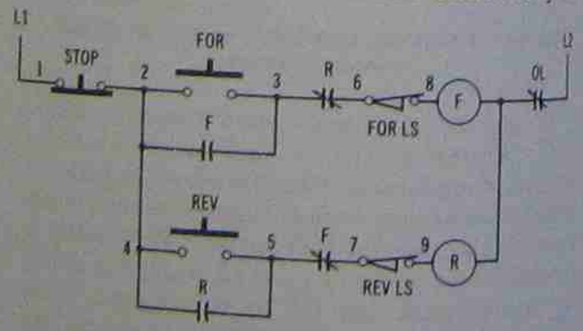
Courtesy Furnas Electric Co.

Fig. 10-7. An instant forward-reverse-stop push-button control circuit.

would, then, be turned off since the circuit from L1 to L2 would be opened. The reverse circuit operates in a similar manner. Two control relays are needed for forward-reverse operation.

The circuit of Fig. 10-7 is the same as the circuit in Fig. 10-6 except for the push-button arrangement. The forward and reverse push buttons are arranged in series. Pressing the "forward" push button automatically opens the reverse circuit and pressing the "reverse" push button automatically opens the forward circuit. Limit switches are also used with this circuit. Their function is the same as in the circuit of Fig. 10-6. In the circuit of Fig. 10-7, when the "forward" push button is pressed, the top push button will momentarily close and the lower push button will momentarily open. When points 2 and 3 are connected, current will flow from L1 to L2 through coil (F). When coil (F) is energized, normally open contact F will close and the normally closed contact F will open. The "forward" coil will, then, remain energized. The reverse push buttons cause a similar action of the reversing circuit. Two control relays are also required.

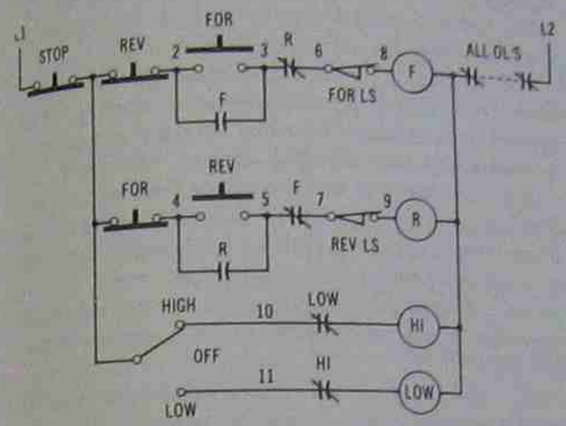
The circuit of Fig. 10-8 is similar in function to that of the circuit in Fig. 10-7. The push-button arrangement of this circuit is simpler. When the normally open forward push button is pressed, current will flow through coil (F). When the forward control relay is



Courtesy Furnas Electric Co.

Fig. 10-8. A forward-reverse-stop push-button control circuit.

energized, normally open contact F will close and normally closed contact F will open. This action will cause a motor to operate in the forward direction. When the normally closed stop push button is pressed, the current through coil (F) is interrupted. When the normally open reverse push button is pressed, current will flow through coil (R). When the reverse coil is energized, normally open contact F will close and normally closed



Courtesy Furnas Electric Co.

Fig. 10-9. Push-button control circuit with a high- and low-speed selector switch.

contact F will open. This action will cause a motor to operate in the reverse direction, until the stop push button is pressed again.

Fig. 10-9 shows a circuit that is another method of forward-reverse-stop control. This control circuit has the added feature of a high- and low-speed selector switch for either the forward or reverse direction. The selector switch is placed in series with the windings of the motor. When the selector is changed from the HIGH position to the LOW position, a modification in the windings of the motor can be made.

There are many other push-button combinations which can be used with control relays to accomplish motor control or control of other types of loads. The circuits discussed in this section represent some basic power control functions such as start-stop, forward-reverse-stop, jogging, and multiple speed control.

MOTOR-STARTING SYSTEMS

The equipment used with motor-starting systems was studied in Chapter 9. Some specific systems used for starting electric motors are discussed in this section.

Function of Magnetic Contactors

Most motor-starting systems utilize one or more magnetic contactors. A schematic diagram of a magnetic contactor circuit used for controlling a single-phase motor is shown in Fig. 10-10. Note that a magnetic contactor relies upon an electromagnetic coil which energizes when current passes through it. The activated coil performs the function of closing a set of normally open contacts. These contacts are connected in series with the power input to the motor that is being controlled.

In Fig. 10-10, the "START" push-button switch is a normally open switch. When the start switch is pressed, current will flow through the coil of the magnetic contactor. This action energizes the coil and the solenoid of the contactor is drawn inward to close the contacts which are in series with the power lines. Once these contacts are closed, current will continue to flow through the electromagnetic coil through the holding contacts (No. 3 in the diagram). Current will continue to flow until the "STOP" push-button switch is pressed. The stop switch is a normally closed switch. When it is pressed, the circuit to the electromagnetic coil is broken. At this time, current no longer flows through the coil. The contacts now release and cause the power lines to be interrupted. Thus, the motor will be turned off. Magnetic contactor circuits are sometimes referred to as across-the-line starters. The relay principle is utilized since a small current through the coil controls a larger current through a motor.

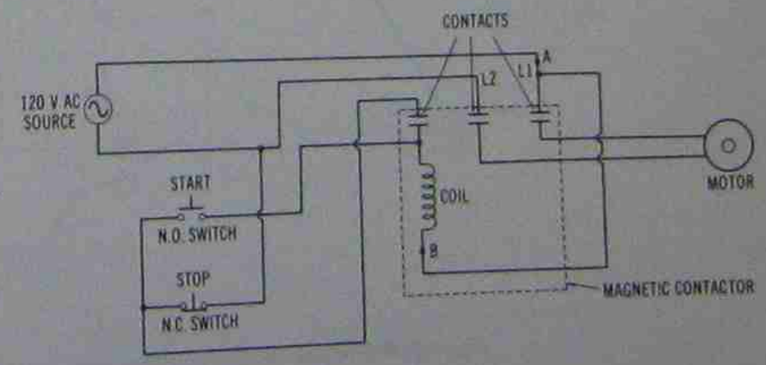


Fig. 10-10. Magnetic contactor motor-control circuit.

Types of Starting Systems

Motor starting, particularly for large motors, can play an important role in the efficient operation of an electrical power system. There are several systems used to start electric motors. The motor-starting equipment that is used is placed between the electrical power source and the motor. Electric motors draw a larger current from the power lines during starting than during normal operation. Motor-starting equipment should attempt to reduce starting currents to a level that can be handled by the electrical power system where they are being used.

Full-Voltage Starting—One method of starting electric motors is called full-voltage starting. This method is the least expensive and the simplest to install. Since full power-supply voltage is applied to the motor initially, maximum starting torque and minimum acceleration time result. However, the power system must be able to handle the starting current drawn by the motor.

Full-voltage starting is illustrated by the diagram of Fig. 10-11. In this power control circuit, a start-stop push-button station is used to control a three-phase motor. When the normally open start push button is pressed, current will flow through the relay coil (M), causing the normally open contacts to close. The line contacts allow full voltage to be applied to the motor when they are closed. When the start push button is released, the relay coil remains energized due to the holding contact. This contact provides a current path from L1 through the normally closed stop push button, through the holding contact, through the coil (M), through a thermal overload relay, and back to L2. When the stop push button is pressed, this circuit is opened causing the coil to be de-energized.

Primary-Resistance Starting—Another motor starting method is called primary-resistance starting. This method uses resistors in series with the power lines to reduce the motor-starting current. Ordinarily, the resistance connected into the power lines may be reduced in steps until full voltage is applied to the motor. Thus, starting current is reduced according to the value of series resistance in the power lines. Since starting torque is directly proportional to the current flow, starting torque is reduced according to the magnitude of current flow.

Fig. 10-12 shows the primary-resistance starting method used to control a three-phase motor. When the

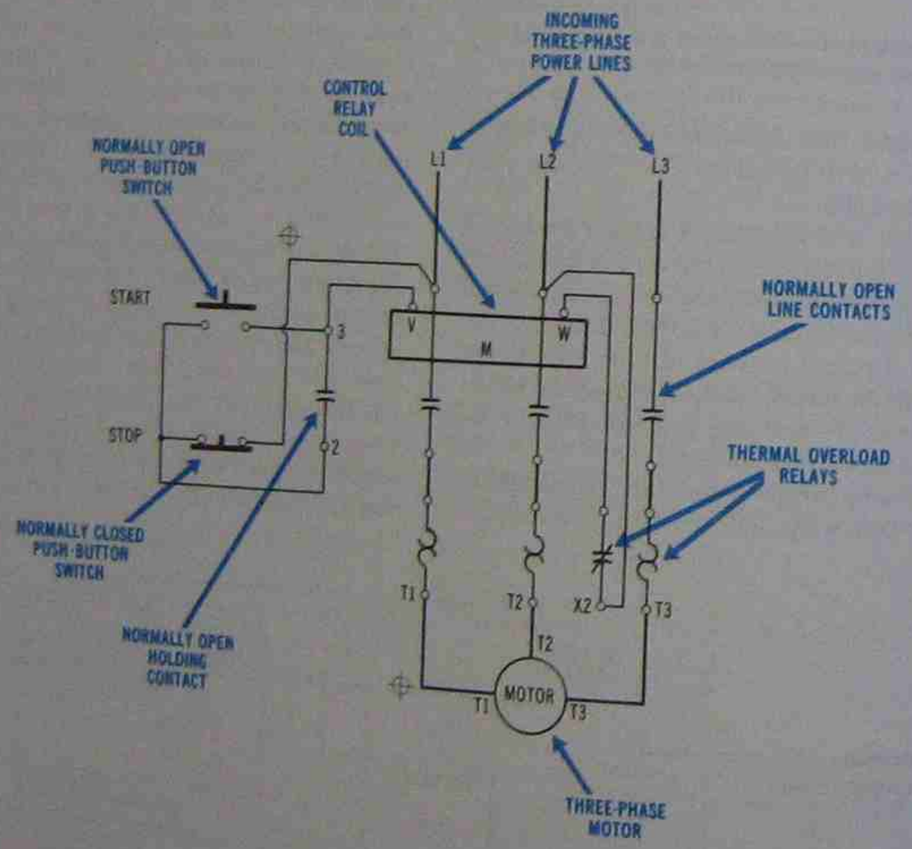


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Fig. 10-11. Full-voltage starting circuit for a three-phase motor.

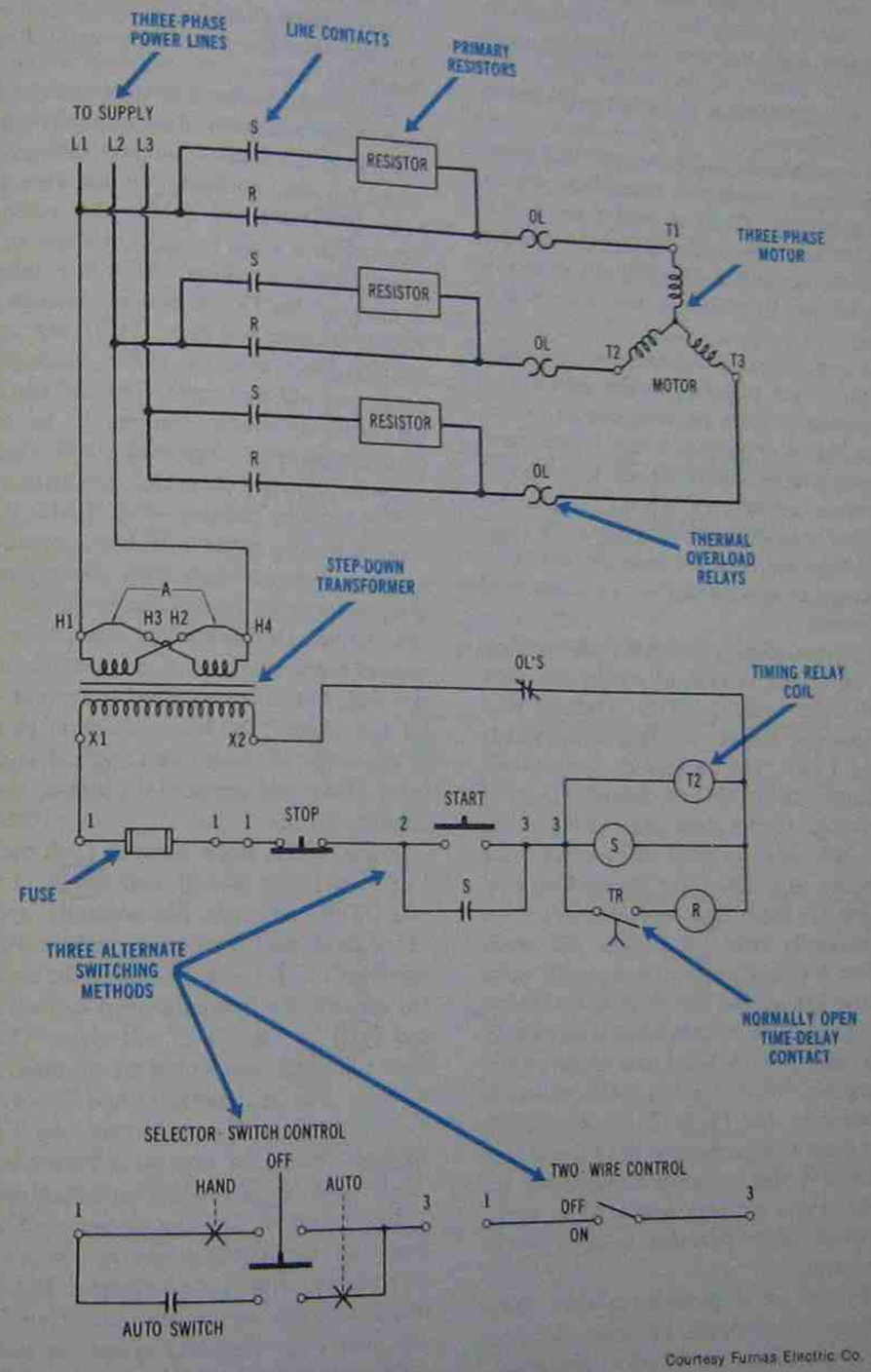

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Fig. 10-12. Primary-resistance starter circuit.

start push button is pressed, coils (S) and (TR) are energized. Initially, the start contacts (S) will close, applying voltage through the primary resistors to the motor. These resistors reduce the value of starting current. Once the time-delay period of timing relay TR has elapsed, contact TR will close. The run contacts (R) will then close and apply full voltage to the motor. Notice that a step-down transformer is used for applying voltage to the control portion of the circuit. This is a commonly used technique for reducing the voltage applied to the relay coils.

Primary-Reactor Starting—Another method, similar to primary-resistance starting is called the primary-reactor starting method. Reactors (coils) are used in place of resistors since they consume smaller amounts of power from the ac source. Usually, this method is more appropriate for large motors that are rated at over 600 volts.

Autotransformer Starting—Autotransformer starting is another method used to start electric motors. This method employs one or more autotransformers to control the voltage that is applied to a motor. The autotransformers used are ordinarily tapped to provide a range of starting-current control. When the motor has accelerated to near its normal operating speed, the autotransformer windings are removed from the circuit. A major disadvantage of this method is the expense of the autotransformers.

An autotransformer starting circuit is shown in Fig. 10-13. This is an expensive type of control that uses three autotransformers and four relays. When the start push button is pressed, current will flow through coils (1S), (2S), and (TR). The 1S and 2S contacts will then close. Voltage will be applied through the autotransformer windings to the three-phase motor. One normally closed and one normally open contact are controlled by timing relay TR. When the specified time period has elapsed, the normally closed TR contact will open and the normally open TR contact will close. Coil (R) will then energize, causing the normally open R contacts to close and apply full voltage to the motor. Normally closed R contacts are connected in series with coils (1S), (2S), and (TR) to open their circuits when coil (R) is energized. When the stop push button is pressed, the current to coil (R) will be interrupted, thus opening the power line connections to the motor. Notice that the 65% taps of the autotransformer are used in Fig. 10-13. There are also taps for 50%, 80%, and 100% to provide more flexibility in reducing the motor-starting current.

Wye-Delta Starting—It is possible to start three-phase motors more economically by using the wye-delta-starting method. Since, in a wye configuration, line current is equal to the phase current divided by 1.73 (or $\sqrt{3}$), it is possible to reduce the starting current by using a wye connection rather than a delta connection. This method, shown in Fig. 10-14, employs a switching arrangement which places the motor windings in a wye configuration during starting and a delta arrangement for running. In this way, starting current is reduced. Although starting torque is reduced, running torque is still high since full voltage appears across each winding when the motor is connected in a delta configuration.

In Fig. 10-14, when the start push button is pressed, coil (S) is energized. The normally open S contacts will close. This action connects the motor windings in a wye (or star) configuration and also activates timing relay (TR) and coil (1M). The normally open 1M contacts then close to apply voltage to the wye-connected motor windings. After the time-delay period has elapsed, the TR contacts will change state. Coil (S) will de-energize and coil (2M) will energize. The S contacts which hold the motor windings in a wye arrangement will then open. The 2M contacts will close and cause the motor windings to be connected in a delta configuration. The motor will, then, continue to run with the motor connected in a delta arrangement.

Part-Winding Starting—Fig. 10-15 shows the part-winding-starting method, which is usually more simple and less expensive than other starting methods. However, motors must be specifically designed to operate in this manner. During starting, the power-line voltage is applied across only part of the parallel-connected motor windings, thus reducing starting current. Once the motor has started, the line voltage is placed across all of the motor windings. This method is undesirable for many heavy-load applications due to the reduction of starting torque.

In Fig. 10-15, when the start push button is pressed, current will flow through coil (M1) of the time-delay relay. This will cause the normally open contacts of M1 to close and a three-phase voltage will be applied to windings T1, T2, and T3. After the time-delay period has elapsed, the normally open contact located below coil (M1) in Fig. 10-15 will close. This action energizes coil (M2) and causes its normally open contacts to close. The M2 contacts then connect the T7, T8, and T9 windings in parallel with the T1, T2, and T3 windings. When the stop push button is pressed, coils (M1) and (M2) will be de-energized.

Direct-Current Starting Systems—Since dc motors have no counterelectromotive force (cemf) when they are not rotating (see Chapter 14), they have tremendously high starting currents. Therefore, they must use some type of control system to reduce the initial starting current. Ordinarily, a series resistance is used. This resistance can be manually or automatically reduced until a full voltage is applied. The four types of control systems commonly used with dc motors are (1) current limit, (2) definite time, (3) counter-emf, and (4) variable voltage. The current-limit method allows the starting current to be reduced to a specified level and, then, advanced to the next resistance step. The definite-time method causes the motor to increase speed in timed intervals with no regard to the amount of armature current or to the speed of the motor. The counter-emf method samples the amount of cemf generated by the armature of the motor to reduce the series resistance accordingly. This method can be used effectively since cemf is proportional to both the speed and the armature current of a dc motor. The variable-voltage method employs a variable direct-current power source to apply a reduced voltage to the motor initially and, then, gradually increase the voltage. No series resistances are needed when the latter method is used.

SPECIALIZED CONTROL SYSTEMS

Electrical power control is usually desired for some specific application. In this section, we will discuss some common types of specialized electrical power control systems that are used today.

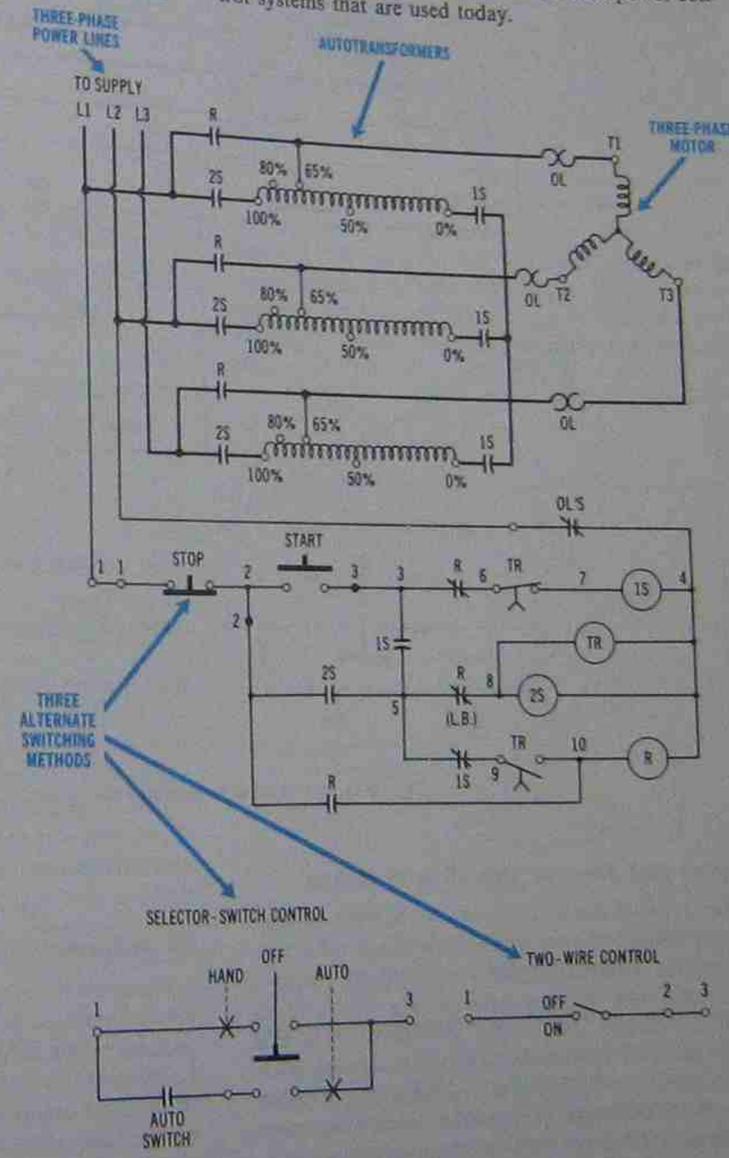

Fig. 10-13. Autotransformer starter circuit used with a three-phase motor.

Courtesy Furnas Electric Co.

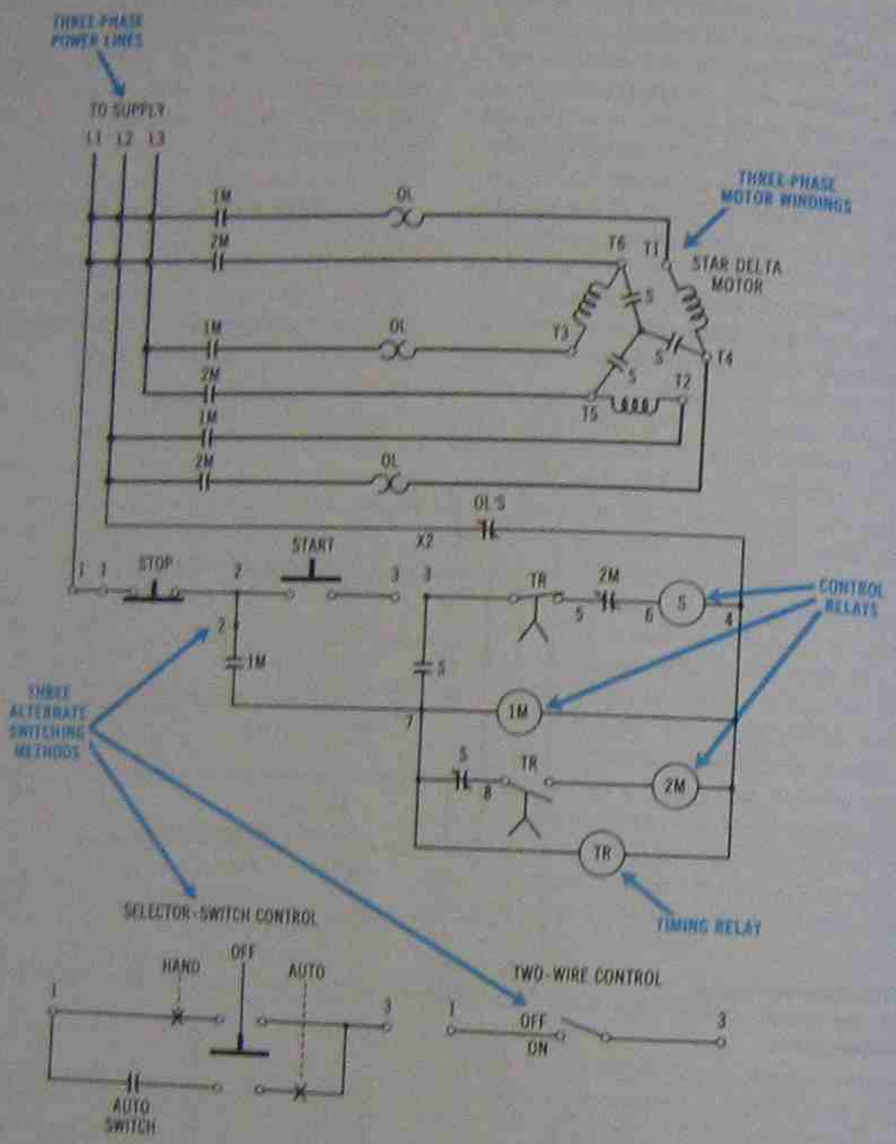

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Fig. 10-14. Wye-to-delta three-phase starter circuit.

Forward and Reverse Operation of Motors

Most types of electrical motors can be made to rotate in either direction by some simple modifications of their connections. Ordinarily, motors require two magnetic contactors, such as those shown in Fig. 10-16, to accomplish forward and reverse operation. These contactors are used in conjunction with a set of three push-button switches—FORWARD, REVERSE, and STOP. When the FORWARD push-button switch is depressed, the forward contactor will be energized. It is deactivated when the STOP push-button switch is depressed. A similar procedure takes place during reverse operation.

Direct-Current Motor Reversing

Direct-current motors can have their direction of rotation reversed by changing either the armature connections *or* the field connections to the power source. In Fig. 10-17, a dc shunt motor-control circuit is shown. When the forward push button is pressed, the F coil will be energized, causing the F contacts to close. The armature circuit is then completed from L1 through the lower F contact, *up* through the armature, through the upper F contact, and back to L2. Pressing the stop push button will de-energize the F coil.

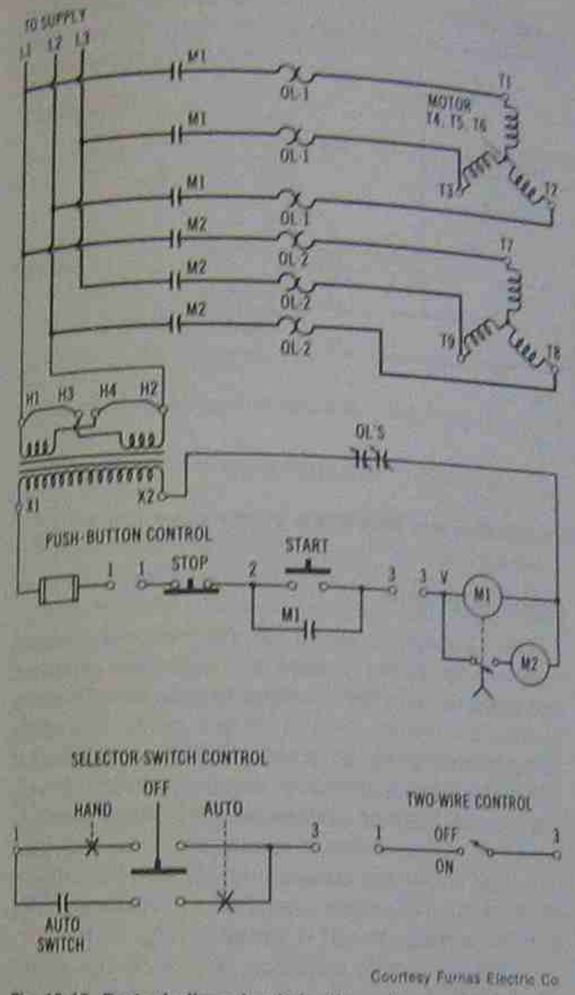

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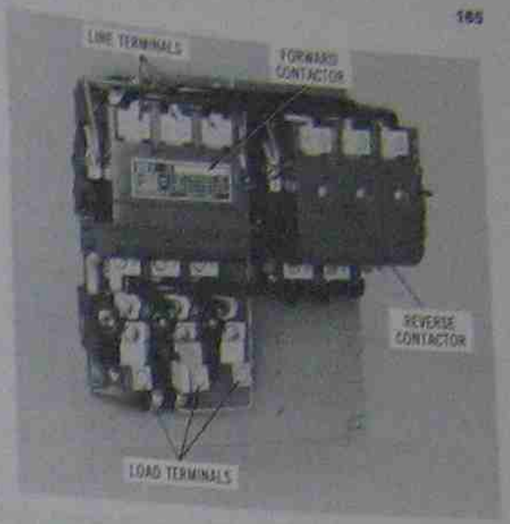
Fig. 10-15. Part-winding circuit for three-phase motor starting.

The direction of rotation of the motor is reversed when the reverse push button is pressed. This is due to the change of the current direction through the armature. Pressing the reverse push button energizes the R coil and closes the R contacts. The armature current path is then from L1 through the upper R contact, *down* through the armature, through the lower R contact, and back to L2. Pressing the stop button will de-energize the R coil.

Single-Phase Induction-Motor Reversing

Single-phase ac induction motors that have start and run windings can have their direction of rotation reversed by using the circuit in Fig. 10-17. If we modify the diagram by replacing the shunt field coils with the run windings and the armature with the start windings,



Courtesy Furnas Electric Co

Fig. 10-16. Reversing magnetic starter.

directional reversal of a single-phase ac motor can be accomplished. Single-phase induction motors are reversed by changing the connections of either the start windings *or* the run windings but not both at the same time.

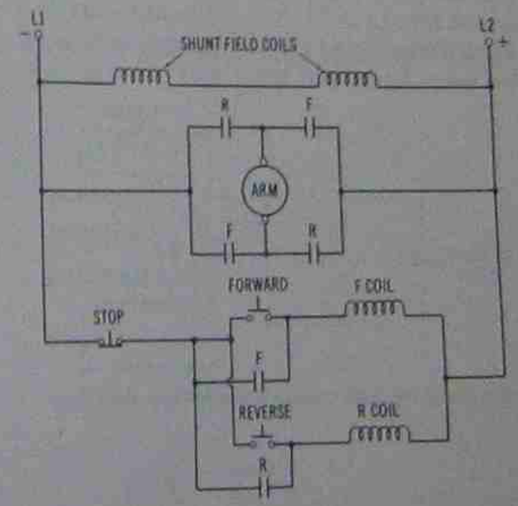


Fig. 10-17. Control circuit for the forward and reverse operation of a dc shunt motor.

Three-Phase Induction-Motor Reversing

Three-phase motors can have their direction of rotation reversed by simply changing the connections of any two power input lines. This changes the phase sequence applied to the motor. A control circuit for three-phase induction-motor reversing is shown in Fig. 10-18.

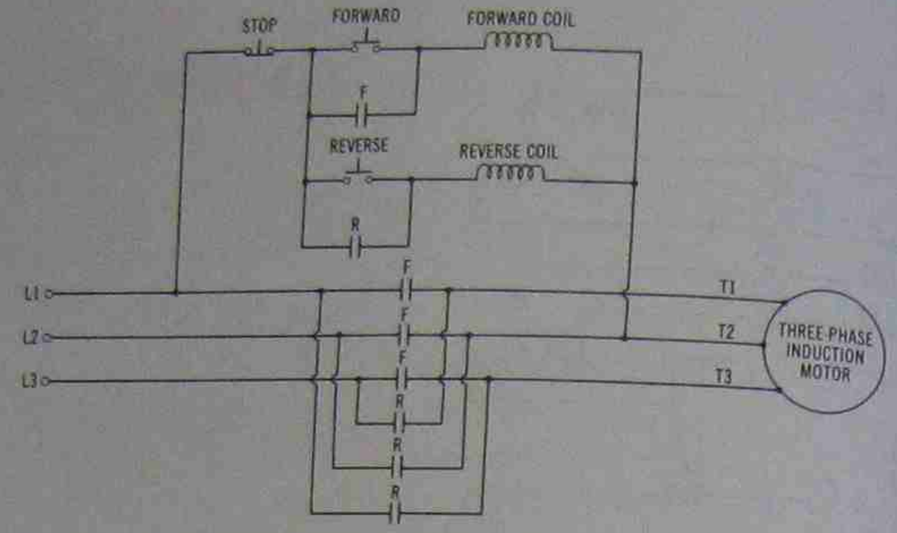


Fig. 10-18. Control circuit for the forward and reverse operation of a three-phase induction motor.

When the forward push button is pressed, the forward coil will energize and close the F contacts. The three-phase voltage is applied from L1 to T1, L2 to T2, and L3 to T3 to cause the motor to operate. The stop push button de-energizes the forward coil. When the reverse push button is pressed, the reverse coil is energized and the R contacts will close. The voltage is then applied from L1 to T3, L2 to T2, and L3 to T1. This action reverses the L1 and L3 connections to the motor and causes the motor to rotate in the reverse direction.

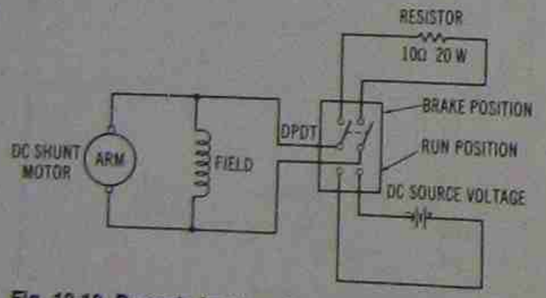


Fig. 10-19. Dynamic braking circuit for a dc shunt motor.

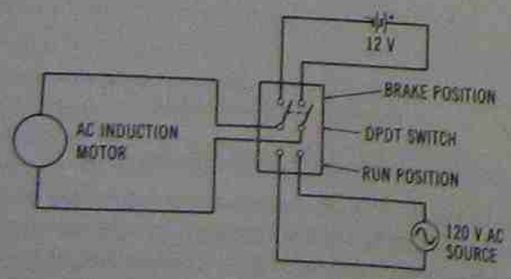


Fig. 10-20. Dynamic braking circuit for a single-phase ac induction motor.

Dynamic Braking

When a motor is turned off, its shaft will continue to rotate for a short period of time. This continued rotation is undesirable for many applications. Dynamic braking is a method used to bring a motor to a quick stop whenever power is turned off. Motors with wound armatures utilize a resistance connected across the armature as a dynamic braking method. When power is turned off, the resistance is connected across the armature. This causes the armature to act as a loaded generator, making the motor slow down immediately. This dynamic braking method is shown in Fig. 10-19.

Alternating-current induction motors can be slowed down rapidly by placing a dc voltage across the winding of the motor. This dc voltage sets up a constant magnetic field which causes the rotor to slow down rapidly. A circuit for the dynamic braking of a single-phase ac induction motor is shown in Fig. 10-20.

Universal Motor Speed Control

An important advantage of a universal ac-dc motor is the ease of speed control. The universal motor has a brush/commutator assembly, with the armature circuit connected in series with the field windings. By varying the voltage applied to universal motors, their speed may be varied from zero to maximum.

The circuit used for this purpose, shown in Fig. 10-21, uses a gate-controlled triac. The triac is a semiconductor device whose conduction may be varied by a trigger voltage applied to its gate. A silicon-controlled rectifier (SCR) could also be used as a speed-control device for a universal motor. Speed-control

circuits like this one are used for many applications, such as electric drills, sewing machines, electric mixers, and industrial applications.

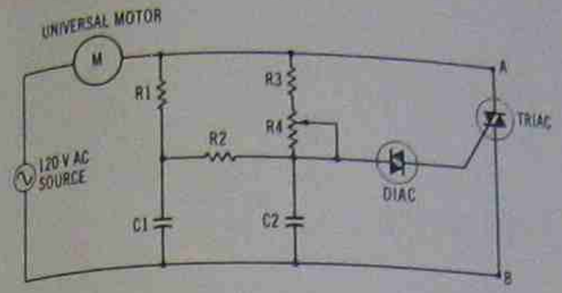


Fig. 10-21. Speed-control circuit for a universal motor.

FREQUENCY-CONVERSION SYSTEMS

The power system frequency used in the United States is 60 hertz or 60 cycles per second. However, there are specific applications that require other frequencies in order to operate properly. Mechanical frequency converters are used to change an incoming frequency into some other frequency. Frequency converters are motor-generator sets that are connected together.

For example, a frequency of 60 Hz could be applied to a synchronous motor which rotates at a specific speed. A generator connected to its shaft could have the necessary number of poles to cause it to produce a frequency of 25 Hz. Recall that frequency is determined by the following relationship:

$$\text{Freq (Hz)} = \frac{\text{Speed of Rotation (rpm)} \times \text{No. of Poles}}{120}$$

A frequency-conversion system is shown in Fig. 10-22. Synchronous units such as the one shown are used wherever precise frequency control is required. It is also possible to design units which are driven by induction motors if some frequency variation can be tolerated.

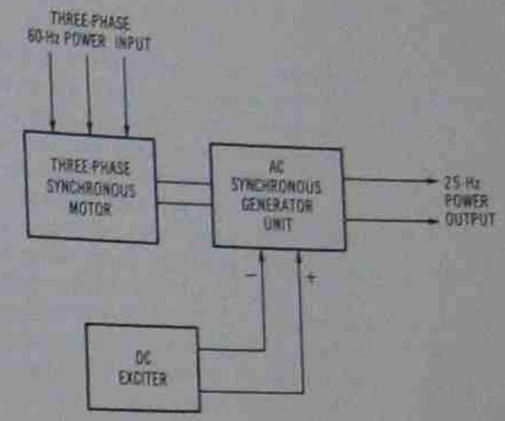


Fig. 10-22. A 60-Hz to 25-Hz frequency-conversion system.

UNIT IV

Power Conversion

One of the most important aspects of electrical power systems is the conversion of electrical power into some other form of energy. Electrical power is ordinarily converted into light, heat, or mechanical energy. The power is converted using either resistive, inductive, or capacitive circuits. The fundamental characteristics of electrical power-conversion systems are discussed in Chapter 11.

The basic types of electrical power-conversion systems are studied further in the remaining chapters. Heat-producing systems are discussed in Chapter 12. Those systems which convert electrical energy into heat energy include resistive, inductive, and capacitive methods. Basic welding methods are also included in this chapter. Chapter 13 deals with the conversion of electrical energy into light energy. Lighting systems include incandescent, fluorescent, and vapor lighting systems. Then, the systems which convert electrical energy into mechanical energy are discussed in Chapter 14. The major mechanical-energy conversion takes place in electric motors. Both direct-current and alternating-current motors are studied in this chapter.

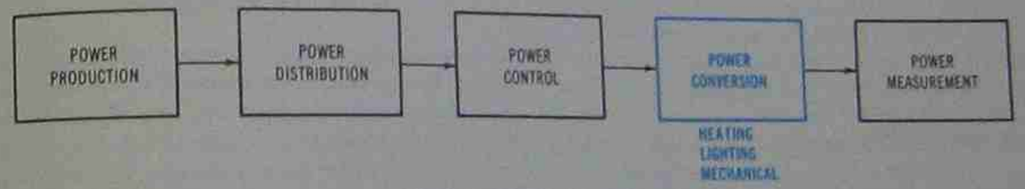


Fig. 4. The Electrical Power System.

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CHAPTER 11

Fundamentals of Electrical Loads

The electrical load devices that are used in industry, in our homes, and in commercial buildings are very important parts of electrical power systems. The load of any system performs a function which involves power conversion. A load converts one form of energy to another form. An electrical load converts electrical energy to some other form of energy, such as heat, light, or mechanical energy. Electrical loads may be classified according to the function which they perform (lighting, heating, mechanical) or by the electrical characteristics which they exhibit (resistive, inductive, capacitive).

LOAD CHARACTERISTICS

In order to plan for power system load requirements, it is necessary to understand the electrical characteristics of all the loads connected to the power system. The types of power supplies and distribution systems which a building uses are determined by the load characteristics. All loads may be considered as either resistive, inductive, capacitive, or a combination of these. We should be aware of the effects which various types of loads will have on the power system. The nature of alternating current causes certain electrical circuit properties to exist.

You should review that portion of Chapter 1 which deals with resistive, inductive, and capacitive effects in an electrical circuit. One primary factor which affects the electrical power system is the presence of inductive loads. These are mainly electric motors. To counteract the inductive effects, utility companies use power-factor corrective capacitors as part of the power system design. Capacitor units are located at substations to improve the power factor of the system. The inductive effect, therefore, increases the cost of a power system and reduces the actual amount of power which is converted to another form of energy.

Load Factor

One electrical load relationship that is important to understand is the *load factor*. Load factor expresses the ratio between the average power requirement and the peak power requirement or:

$$\text{load factor} = \frac{\text{average demand (kW)}}{\text{peak demand (kW)}}.$$

The average demand for an industry or commercial building is the average electrical power used over a specific time period. The peak demand is the maximum amount of power (kW) used during that time period. The load profile shown in Fig. 11-1 shows a typical industrial demand versus the time curve for a working day. Demand peaks that far exceed the average demand cause a decrease in the load factor ratio. Low load factors result in an additional billing charge by the utility company.

Utility companies must design power distribution systems to meet the peak demand time and insure that their generating capacity will be able to meet this peak power demand. Therefore, it is inefficient electrical design for an industry to operate at a low load factor, since this represents a significant difference between peak power demand and average power demand. Every industry should attempt to raise its load factor to the maximum level it can. By minimizing the peak demands of industrial plants, power demand control systems and procedures can help increase the efficiency of our nation's electrical power systems.

Be careful not to confuse the load factor of a power system with the power factor. Power factor was discussed in Chapter 1. The power factor is the ratio of power converted (true power) to the power delivered to a system (apparent power). If necessary, you should review power factor.

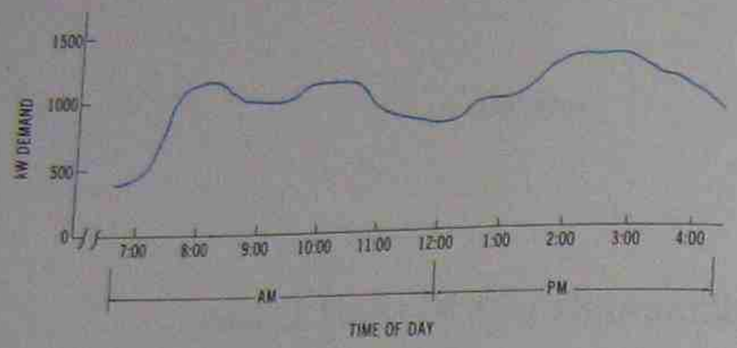


Fig. 11-1. Load profile for an industrial plant.

Power Factor Correction

Most industries use a large number of electric motors; therefore, industrial plants represent highly inductive loads. This means that industrial power systems operate at a power factor of less than unity (1.0). However, it is undesirable for an industry to operate at a low power factor, since the electrical power system will have to supply more power to the industry than is actually used.

A given value of volt-amperes (voltage × current) is supplied to an industry by the electrical power system. If the power factor (pf) of the industry is low, the current must be higher since the power converted by the total industrial load equals VA × pf. The value of power factor decreases as the reactive power (unused power) drawn by the industry increases. This is shown in Fig. 11-2. We will assume a constant value of true power to see the effect of increases in reactive power drawn by a load. The smallest reactive power shown (var_1) results in the volt-ampere value of VA_1. As reactive power is increased, as shown by the var_2 and var_3 values, more volt-amperes (VA_2 and VA_3) must be drawn from the source. This is true since the voltage component of the supplied volt-amperes remains constant. This example represents the same effect as a decrease in the power factor, since pf = W/VA, and as VA increases, the pf will decrease if W remains constant.

Utility companies usually charge industries for operating at power factors below a specified level. It is desirable for industries to "correct" their power factor to avoid such charges and to make more economical use of electrical energy. Two methods may be used to cause the power factor to increase: (1) power factor-corrective capacitors, and (2) three-phase synchronous motors. Since the effect of capacitive reactance is opposite to that of inductive reactance, their reactive effects will counteract one another. Either power factor-corrective capacitors or three-phase synchronous motors may be used to add the effect of capacitance to an ac power line. Some pole-mounted power factor-corrective capacitors are shown in Fig. 11-3.

An example of power factor correction is shown in Fig. 11-4. We will assume from the example that both true power and inductive reactive power remain constant at values of 10 kW and 10 kvar. In Fig. 11-4A, the formulas show that the power factor equals 70%. However, if 5-kvar capacitive reactive power in introduced into the electrical power system, the net reactive power becomes 5 kvar (10-kvar inductive minus 5-kvar capacitive), as shown in Fig. 11-4B. With the addition of 5-kvar capacitive to the system, the power factor is increased to 89%. Now, in Fig. 11-4C, if 10-kvar capacitive is added to the power system, the total reactive power (kvar) becomes zero. The true power is now equal to the apparent power; therefore, the power factor is 1.0, or 100%, which is characteristic of a

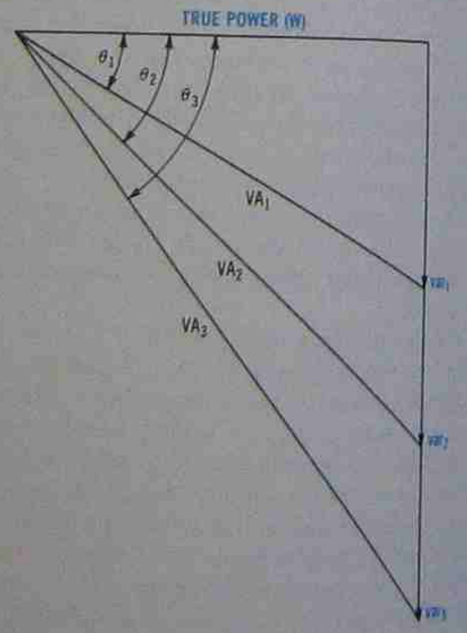


Fig. 11-2. Effect of increases in reactive power (var) on apparent power (VA).

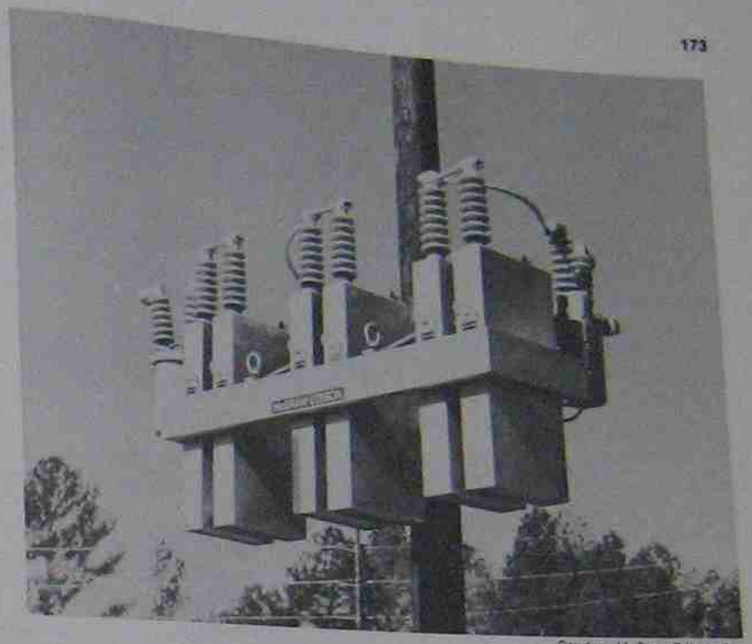


Fig. 11-3. Pole-mounted, power factor-corrective capacitors.

Courtesy McGraw-Edison Co.

purely resistive circuit. The effect of the increased capacitive reactive power in the system is to increase or "correct" the power factor and, thus, reduce the current drawn from the power distribution lines that supply the loads. In many cases, it is beneficial for industries to invest in either power factor-corrective capacitors or three-phase synchronous motors to correct their power factor.

Utility companies also attempt to correct the power factor of the power distribution system. A certain quantity of inductance is present in most of the power distribution system, including the generator windings, the transformer windings, and the power lines. To counteract the inductive effects, utilities use power factor-corrective capacitors, such as the pole-mounted units shown in Fig. 11-3.

Capacitors for Power Factor Correction

Static capacitors are used for power factor correction in the system. They are constructed similar to the smaller capacitors used in electrical equipment that have metal-foil plates separated by paper insulation. Ordinarily, static capacitors are housed in metal tanks, so that the plates can be immersed in an insulating oil to improve high-voltage operation. The usual operating voltages of static capacitors is from 230 volts to 13.8 kilovolts. These units are connected in parallel with power lines, usually at the industrial plants, to increase the system power factor. Their primary disadvantage is that their capacitance cannot be adjusted to compensate for changing power factors.

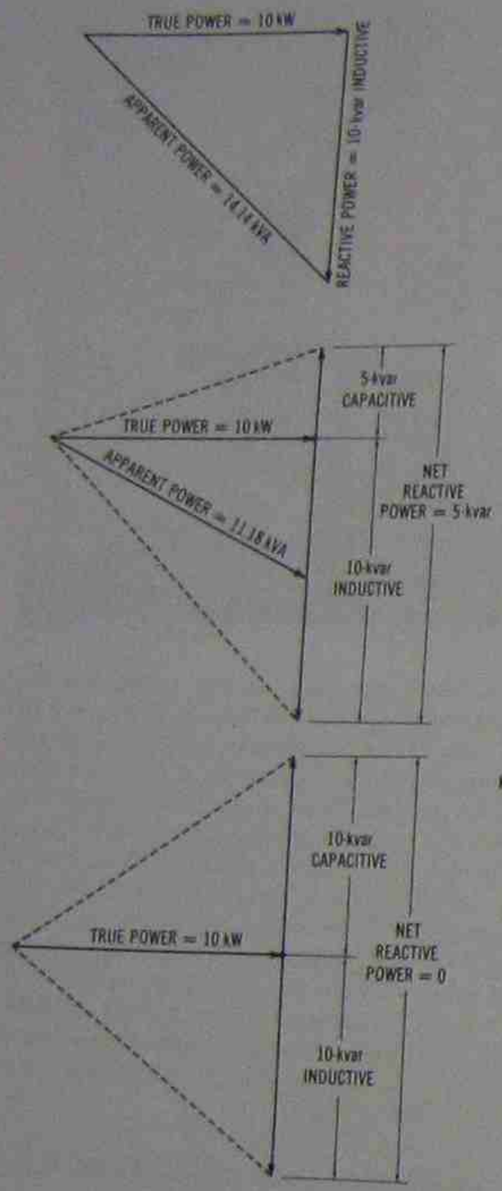
Power factor correction can also be accomplished by using *synchronous capacitors* connected across the power lines. (Three-phase synchronous motors are also called synchronous capacitors; see Chapter 14 for a discussion of three-phase synchronous motors.) The advantage of synchronous capacitors over static capacitors is that their capacitive effect can be adjusted as the system power factor increases or decreases. The capacitive effect of a synchronous capacitor is easily changed by varying the dc excitation voltage applied to the rotor of the machine. Industries considering the installation of either static or synchronous capacitors should first compare the initial equipment cost and the operating cost against the savings brought about by an increased system power factor.

THREE-PHASE LOAD CHARACTERISTICS

In Chapter 1, single-phase circuit fundamentals were thoroughly discussed. However, the major type of load in electrical power systems is the three-phase load. Therefore, you should become familiar with the characteristics of three-phase loads.

Balanced Three-Phase Loads

A balanced three-phase load means that the resistance or impedances connected across each phase of the system are equal. Three-phase motors are one type of balanced load. The following relationships exist in a balanced three-phase delta system. The line voltages (V_L) are equal to the phase voltages (V_P). The line



$$kVA = \sqrt{kW^2 + kvar^2}$$
$$= \sqrt{10^2 + 10^2}$$
$$= \sqrt{100 + 100}$$
$$= \sqrt{200}$$
$$= 14.14$$
$$pf = \frac{\text{TRUE POWER}}{\text{APPARENT POWER}}$$
$$= \frac{10\ kW}{14.14\ kVA}$$
$$= 0.7\ (70\%)$$

(A) Reactive power = 10-kvar inductive.

$$kVA = \sqrt{kW^2 + kvar^2}$$
$$= \sqrt{10^2 + 5^2}$$
$$= \sqrt{100 + 25}$$
$$= \sqrt{125}$$
$$= 11.18$$
$$pf = \frac{\text{TRUE POWER}}{\text{APPARENT POWER}}$$
$$= \frac{10\ kW}{11.18\ kVA}$$
$$= 0.89\ (89\%)$$

(B) Reactive power = 10-kvar inductive, 5-kvar capacitive.

$$kVA = \sqrt{kW^2 + kvar^2}$$
$$= \sqrt{10^2 + 0}$$
$$= \sqrt{100}$$
$$= 10$$
$$pf = \frac{\text{TRUE POWER}}{\text{APPARENT POWER}}$$
$$= \frac{10\ kW}{10\ kVA}$$
$$= 1.0\ (100\%)$$

(C) Reactive power = 10-kvar inductive, 10-kvar capacitive.

Fig. 11-4. Illustration of the effect of capacitive reactance on an inductive load.

currents (I_L) are equal to the phase currents (I_P) multiplied by 1.73. Thus:

$$V_L = V_P$$
$$I_L = I_P \times 1.73$$

For a balanced three-phase wye system, the method used to find the voltages and currents is similar. The voltage across the ac lines (V_L) is equal to the square root of 3 (1.73) multiplied by the voltage across the phase windings (V_P), or

$$V_L = V_P \times 1.73.$$

The line currents (I_L) are equal to the phase currents (I_P), or

$$I_L = I_P.$$

The power developed in each phase (P_P) for either a wye or a delta circuit is expressed as:

$$P_P = V_P \times I_P \times pf,$$

where,

pf is the power factor (phase angle between voltage and current) of the load.

The total power developed by all three phases of a three-phase generator (P_T) is expressed as:

$$P_T = 3 \times P_P$$
$$= 3 \times V_P \times I_P \times pf$$
$$= 1.73 \times V_L \times I_L \times pf.$$

As an example, we can calculate the phase current (I_P), line current (I_L), and total power (P_T) for a 240-volt three-phase delta-connected system with 1000-watt load resistances connected across each power line. The phase current is:

$$I_P = \frac{P_P}{V_P}$$
$$= \frac{1000\ \text{watts}}{240\ \text{volts}}$$
$$= 4.167\ \text{amperes}$$

The line current is calculated as:

$$I_L = I_P \times 1.73$$
$$= 4.167 \times 1.73$$
$$= 7.21\ \text{amperes.}$$

Thus, the total power is determined as:

$$P_T = 3 \times P_P$$
$$= 3 \times 1000\ \text{watts}$$
$$= 3000\ \text{watts.}$$

Another way to calculate the total power is:

$$P_T = 1.73 \times V_L \times I_L \times pf$$
$$= 1.73 \times 240\ \text{volts} \times 7.21\ \text{amperes} \times 1$$
$$= 2993.59\ \text{watts}$$

(Note that your answer depends upon the number of decimal places to which you carry your calculations. Round off I_L at 7.2 amperes and your answer for the last calculation is 2989.44 watts, instead of 2993.59 watts.)

The following is an example of the power calculation for a three-phase wye system. For the problem, "find the line current (I_L) and power per phase (P_P) of a balanced 20,000-watt 277/480-volt three-phase wye system operating at a 0.75 power factor," we use the formula

$$P_T = V_L \times I_L \times 1.73 \times pf.$$

Transposing and substituting, we have:

$$I_L = \frac{P_T}{V_L \times 1.73 \times pf}$$
$$= \frac{20{,}000\ \text{watts}}{480\ \text{volts} \times 1.73 \times 0.75}$$
$$= 32.11\ \text{amperes}$$

Then, for the power per phase (P_P), divide the 20,000 watts of the system by 3 (the number of phases) for a value of 6,666.7 watts (6.66 kW).

Unbalanced Three-Phase Loads

Often, three-phase systems are used to supply power to both three-phase and single-phase loads. If three identical single-phase loads were connected across each set of power lines, the three-phase system would still be balanced. However, this situation is usually difficult to accomplish, particularly when the loads are lights. Unbalanced loads exist when the individual power lines supply loads that are not of equal resistances or impedances.

The total power converted by the loads of an unbalanced system must be calculated by looking at each phase individually. Total power of a three-phase unbalanced system is:

$$P_T = P_{P\text{-}A} + P_{P\text{-}B} + P_{P\text{-}C}$$

where the power-per-phase (P_P) values are added. Power per phase is found in the same way as when dealing with balanced loads:

$$P_P = V_P \times I_P \times \text{power factor.}$$

The current flow in each phase may be found if we know the power per phase and the phase voltage of the system. The phase currents are found in the following manner:

1. The following 120-volt single-phase loads are connected to a 120/208-volt wye system. Phase A has 2000 watts at a 0.75 power factor, Phase B has 1000 watts at a 0.85 power factor, and Phase C has 3000 watts at a 1.0 power factor. Determine the total power of the three-phase system and the current flow through each line.
2. To find the phase currents, use the formula $P_P = V_P \times I_P \times$ power factor, and transpose. Thus, we have $I_P = P_P/V_P \times pf$. Substitution of the values for each leg of the system gives us:

a. $$I_{P\text{-}A} = \frac{P_{P\text{-}A}}{V_P \times pf}$$
$$= \frac{2000\ \text{watts}}{120\ \text{volts} \times 0.75}$$
$$= 22.22\ \text{amperes}$$

b. $$I_{P\text{-}B} = \frac{P_{P\text{-}B}}{V_P \times pf}$$
$$= \frac{1000\ \text{watts}}{120\ \text{volts} \times 0.85}$$
$$= 9.8\ \text{amperes}$$

c. $$I_{P\text{-}C} = \frac{P_{P\text{-}C}}{V_P \times pf}$$
$$= \frac{3000 \text{ watts}}{120 \text{ volts} \times 1.0}$$
$$= 25.0 \text{ amperes}$$

3. To determine the total power, use the total power formula for a three-phase unbalanced system that was just given.

$$P_T = P_{P\text{-}A} + P_{P\text{-}B} + P_{P\text{-}C}$$
$$= 2000 + 1000 + 3000$$
$$= 6000 \text{ watts } (6 \text{ kW})$$

The measurement of power in balanced and unbalanced three-phase systems is discussed further in Unit V.

PROBLEMS

1. Calculate the load factor of a commercial building which has an average power demand of 500 kW per day and a peak power demand of 625 kW.

2. This problem shows the effect of power factor correction.

   a. A series circuit has a resistance of 20 ohms and an inductive reactance of 30 ohms. The circuit has 100 volts applied. Calculate: (A) Z, (B) I, (C) apparent power, (D) true power, and (E) power factor.

   b. Assume that a capacitor with a capacitive reactance of 20 ohms was added into the above series circuit. Calculate: (A) total reactance, (B) Z, (C) I, (D) apparent power, (E) true power, and (F) power factor.

   c. This problem shows that when capacitance is added to an inductive circuit, total reactance _____, total impedance _____, current _____, apparent power _____, true power _____, and the power factor _____. (Insert increases or decreases in the blank spaces.)

3. A single-phase 240-volt motor load converts 1250 watts of electrical power. The line current of the motor is 9.1 amperes. Calculate: (A) apparent power, (B) power factor, and (C) reactive power.

4. The current through each line of a 240-volt delta system is 10 amperes with a resistive load. Calculate: (A) phase current, (B) power per phase, and (C) total power.

5. A 120/208-volt balanced three-phase system has line currents of 60 amperes and a power factor of 0.75. Calculate: (A) power per phase and (B) total power.

6. A 277/480-volt balanced three-phase system has three loads connected to it, each rated at 10 kW. The system power factor is 0.85. Calculate: (A) total power and (B) current through each line.

CHAPTER 12

Heat-Producing Systems

Power conversion systems are commonly referred to by the function they perform. Power conversion takes place in the *load* of an electrical power system. Common types of power system loads are those which convert electrical energy into heat, light, or mechanical energy. There are various types of lighting, heating, and mechanical loads used in industry, commercial buildings, and homes. Several of these power conversion systems will be discussed in Chapters 12, 13, and 14.

BASIC HEAT-PRODUCING LOADS

Most loads that are connected to electrical power systems produce a certain amount of heat, mainly due to current flow through resistive devices. In many instances, heat represents a power loss in the circuit, since heat energy is not the type of energy that was to be produced. Lights, for instance, produce heat energy as well as light energy. The conversion of electrical energy to heat energy in a light-producing load reduces the efficiency of that load device, since not all of the available source energy is converted to light energy. There are, however, several types of power conversion systems which are mainly heat-producing loads. Their primary function is to convert electrical energy into heat energy. Some basic systems include resistance heating, inductive heating, and dielectric (capacitive) heating.

Resistance Heating

Heat energy is produced when an electrical current flows through a resistive material. In many instances, the heat energy produced by an electrical current is undesirable; however, certain applications require controlled resistance heating. Useful heat may be transferred from a resistive element to a point of utilization by the common methods of heat transfer—convection, radiation, or conduction. A heating-element enclosure is needed to control the transfer of heat by convection and radiation. For heat transfer by conduction, the heating element is in direct contact with the material to be heated. Actual heat transfer usually involves a combination of these methods.

Fig. 12-1 illustrates the principle of resistance heating. The self-contained heating element uses a coiled resistance wire which is placed inside a heat-conducting material and enclosed in a metal sheath. This principle may be used to heat water, oil, the surrounding atmosphere, or various other media. This type of heater

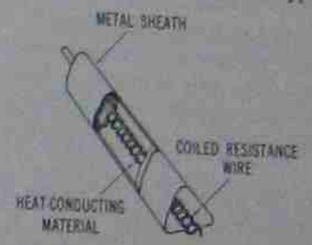


Fig. 12-1. Resistance heating principle.

may be employed in the open air or immersed in the media to be heated. The useful life of the resistance elements depends mainly upon the operating temperature. As the temperature increases, the heat output also increases. Basically, the heat energy produced is dependent upon the current flow and the resistance of the element and can be calculated as current squared times resistance (I^2R).

Induction Heating

The principle of induction heating is illustrated in Fig. 12-2. Heat is produced in magnetic materials when they are exposed to an alternating-current field. In the example shown, current is induced in the material heated by electromagnetic induction. This is brought about by the application of an alternating current to the heating coil. The material to be heated must be a *conductor* in order for current to be induced. Ordinarily, a high-frequency ac source in the range of 100-

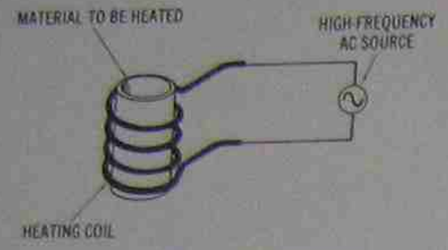


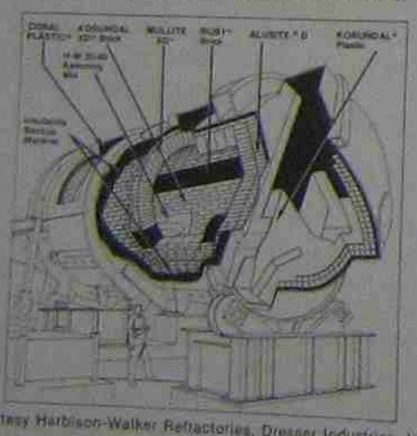
Fig. 12-2. Induction heating principle.

500 kHz is used to produce a higher heat output. This higher heat output is due to greater amounts of induced voltage.

As the magnetic field created by the high-frequency ac source moves across the material to be heated, the induced voltage causes *eddy currents* (circulating currents) to flow in the material. Heat results due to the resistance of the material to the flow of the eddy currents. The heat produced by this method is rapid and thus advantageous.

The major application of the induction-heating process is in metalworking industries for such processes as hardening, soldering, melting, and annealing of metals. The heat produced by this process is extremely rapid compared to other methods of heating. The area of the metal that is actually heated can be controlled by the size and position of the heating coils of the induction heater. This type of control is difficult to accomplish by other methods. Induction furnaces, such as the one shown in Fig. 12-3, use the induction-heating principle.

By varying the frequency of the voltage applied to the induction heater windings, it is possible to vary the depth of heat penetration into the heated metal. At higher frequencies, due to the so-called "skin effect," the heat produced by the induced current from the heating coils will not penetrate as deeply. Thus, heat will penetrate more deeply at lower frequencies. When heat must be localized into the surface of a material only, such as for surface hardening of a metal, higher frequencies are used. The cost of higher frequency induction heaters is greater due to the more complex oscillator circuits required to produce these frequencies.



Courtesy Harbison-Walker Refractories, Dresser Industries, Inc.

Fig. 12-3. Illustration of an induction furnace.

Dielectric (Capacitive) Heating

Induction heating can only be used with conductive materials. Therefore, some other method must be used to heat nonconductive materials. Such a method is illustrated in Fig. 12-4, and is referred to as *dielectric* or *capacitive* heating. Nonconductors may be heated by placing them in an electrostatic field created between two metal electrodes that are supplied by a high-frequency ac source. The material to be heated becomes the dielectric or insulation of a capacitive device. The metal electrodes constitute the two plates.

When high-frequency ac is applied to a dielectric heating assembly, the changing nature of the applied ac causes the internal atomic structure of the dielectric material to become distorted. As the frequency of the ac increases, the amount of internal atomic distortion also increases. This internal friction produces a large amount of heat in the nonconductive material. Frequencies in the 50-MHz range may be used for dielectric heating. Dielectric heating produces a rapid heat which is spread throughout the heated material. Common applications of this heating method are the gluing of plywood and the bonding together of plastic sheets.

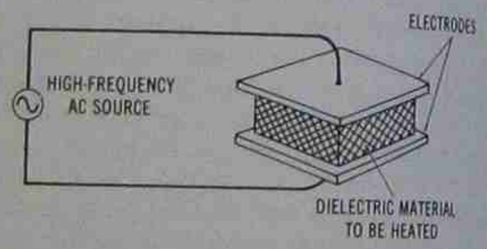


Fig. 12-4. Capacitive heating principle.

ELECTRICAL WELDING

Electrical welding is another common type of heat-producing power conversion system. The types of electrical welding systems include resistance welding, electric arc welding, and induction welding.

Resistance Welding

Several familiar welding methods, such as spot welding, seam welding, and butt welding, are resistance welding processes. All of these processes rely upon the resistance heating principle. Spot welding, illustrated in Fig. 12-5A, is performed on overlapping sheets of metal, which are usually less than ¼-inch thick. The metal sheets are clamped between two electrodes and an electrical current is passed through the electrodes and metal sheets. The current causes the metals to fuse together. The instantaneous current through the electrodes is usually in excess of 5000 amperes, while the voltage between the electrodes is less than 2 volts.

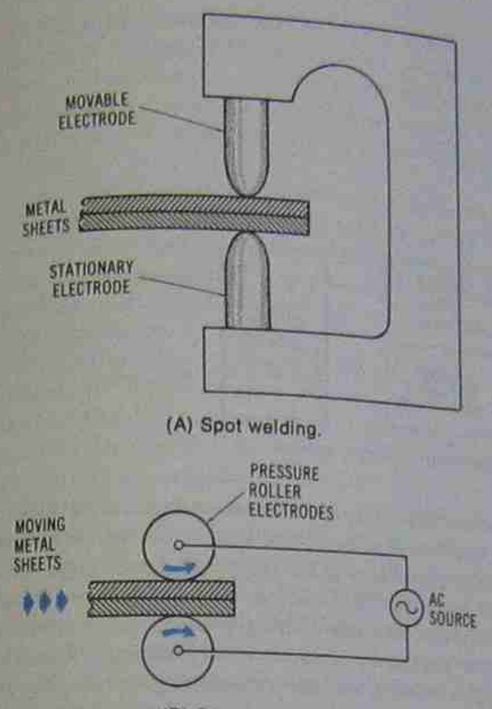


Fig. 12-5. Resistance welding methods.

Seam welding, shown in Fig. 12-5B, is accomplished by passing sheets of metal through two pressure rollers while a continuously interrupted current is passed through the electrodes. The operational principle of seam welding is the same as spot welding. Several other similar methods, which are referred to as butt welding, edge welding, and projection welding are also commonly used.

Electric Arc Welding

While resistance welding utilizes pressure on the materials to be welded, electric arc welding produces welded metals by localized heating without pressure, as shown in Fig. 12-6. An electric arc is created when the electrode of the welder is brought in contact with the metal to be welded. Carbon electrodes are used for direct-current or alternating-current arc welding of nonferrous metals and alloys. Not all metals can be welded by the arc-welding process. The welding metal is produced by melting part of the metal that is to be welded. This method pool is added to, when necessary, by the use of a filler rod. The puddle (molten metal pool) then fills in the gap (arc crater) that was created by the arc of the electrode. Various types and various current-voltage ratings of electric arc welders are available.

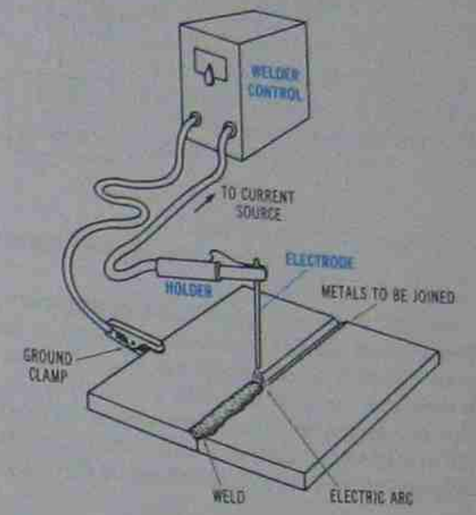


Fig. 12-6. Electric arc welding.

A smaller amount of current is required for arc welding than for resistance welding. The currents may range from 50 to 200 amperes or higher for some applications. Voltages typically range from 10 to 50 volts. An electric arc welder may be supplied by a portable generator, a storage-battery unit, a step-down transformer, or a rectification unit.

Induction Welding

The induction welding process uses the principle of induction heating to fuse metals together. High-frequency alternating current is applied to a heating coil into which the materials to be welded are placed. Tubular metal is often welded in this way.

Power Considerations for Electric Welders

Electric welders are rather specialized types of equipment since they use very high amounts of current at low voltage levels. They have a peculiar effect on the power system operation. They draw large amounts of current for short periods of time. Ignitrons or SCRs are commonly used to control the starting and stopping of the large currents associated with electric welders. The current rating of these devices must be very high, sometimes in the range of 1000 to 100,000 amperes, and the power distribution equipment must be able to handle these high currents.

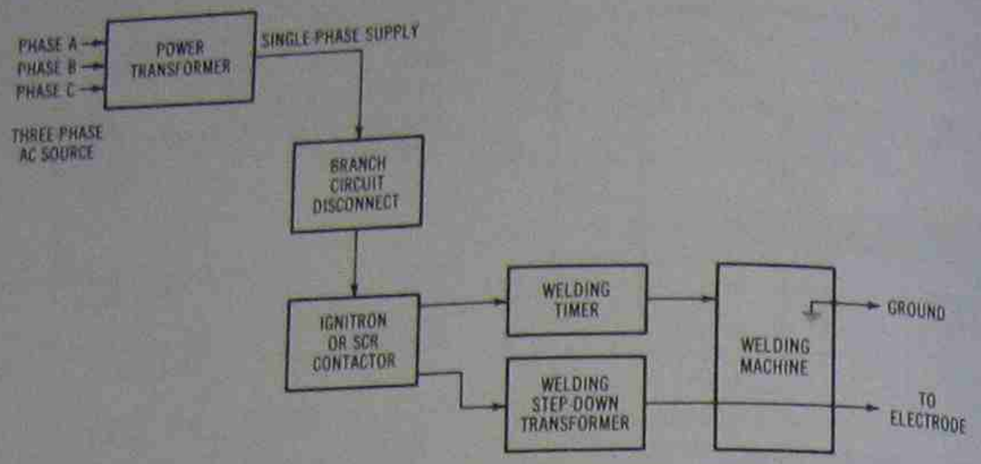


Fig. 12-7. Block diagram of a typical electric welding system.

Fig. 12-7 illustrates a typical electric welding system. The ac power supplied from the branch circuit of the power system is either stepped down by a transformer to deliver ac voltage to the welder or rectified to produce dc voltage for direct-current welders. In either type of machine, an ignitron or SCR contactor is ordinarily used to control the on and off time of the welder.

Ignitron Contactors

Ignitron tubes are commonly used to control the large currents of welders. The circuit shown in Fig. 12-8 is an ignitron contactor used to turn a welder on and off. One ignitron will conduct during each alternation of the ac source voltage. Ignitron contactors serve the same purpose in welding circuits that magnetic contactors perform in electric motor control. They merely serve as switching devices for very large currents.

SCR Contactors

Silicon-controlled rectifier (SCR) contactors are now replacing their ignitron counterparts. Since SCRs can now be designed to handle large amounts of current, they are usually more desirable to use than ignitrons. If we replaced the ignitrons in Fig. 12-8 with SCRs, the result would be an SCR contactor circuit. The SCRs are triggered or turned on by pulses supplied by the timing or sequencing circuits of the welder. The SCRs, as well is ignitrons, are usually cooled by circulating water.

ELECTRIC HEATING AND AIR-CONDITIONING SYSTEMS

A very important type of electrical power conversion is that which takes place in the heating and air-conditioning systems of homes, industries, and commercial buildings. These loads convert a high percentage of the total amount of electrical power that is furnished. Although natural gas and fuel-oil heating systems are still used, electrical heating is becoming more prevalent each year. Air-conditioning systems are also becoming more commonly used to cool buildings. The use of electric heating and air-conditioning systems has made us even more dependent upon electrical power. We now use electrical power to maintain a comfortable environment inside buildings.

Basics of Electric Heating

There are several important factors which must be understood in order to have a knowledge of electric heating. Heat is measured in *British thermal units* (*Btu's*). One Btu is the amount of heat required to raise the temperature of one pound of water one degree Fahrenheit. Heat energy is the amount of 3.4 Btu's per hour is equivalent to one watt of electrical energy.

Another basic factor to be considered in the study of electric heating is called *design temperature difference*. This is the difference between inside and outside temperatures in degrees Fahrenheit. The outside temperature is considered to be the *lowest* temperature which is expected to occur *several* times a year. The inside temperature is the desired temperature (thermostat setting).

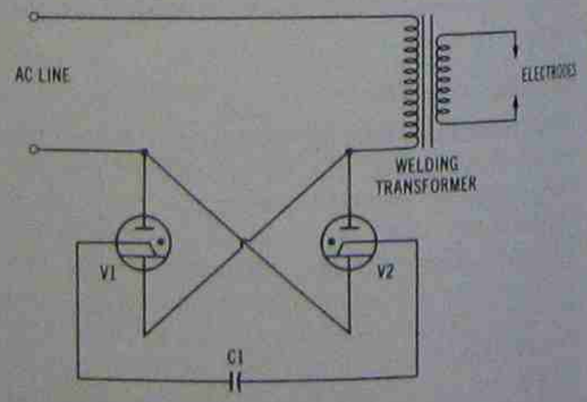


Fig. 12-8. An ignition contactor circuit.

A factor used in conjunction with design temperature difference is called *degree days*. The degree-day factor is used to determine the average number of degrees that the mean temperature is below 65° F. This data is averaged over seasonal periods for consideration in insulating buildings.

The insulation of a building is a very important consideration in electric heating systems. Insulation is used to oppose the escape of heat. The quality of insulation is expressed by a *thermal resistance* factor (R). The total thermal resistance of a building is found by considering the thermal resistance of the entire structure (wood, concrete, insulation, etc.). The inverse of thermal resistance is called the *coefficient of heat transfer* (U), which is an expression of the amount of heat flow through an area expressed in Btu per square foot per hour per degree Fahrenheit. The following formulas are used in the conversion of either U or R to electrical units (watts):

$$\text{Thermal resistance} = \frac{1}{\text{Coefficient of heat transfer}}$$

$$\text{Watts} = \frac{\text{Coefficient of heat transfer}}{3.4}$$

or,

$$\text{Watts} = 0.29 \times \text{U}$$

Importance of Insulation

The manufacturers of insulation can supply various tables which can be used to estimate the heat loss that can occur in buildings of various types of construction. A heat loss occurs, particularly through the windows and doors of buildings. The periodic use of doors has a considerable effect on heat loss also. A building must have sufficient insulation to reduce heat loss, otherwise, electrical heating and air-conditioning systems will be very inefficient. The heat loss of a building depends primarily upon the building construction and the design temperature difference factor where the building is located. Buildings made of concrete have a different amount of heat loss than those made of a wood-frame construction. Heat loss will occur through the walls, floors, windows, and ceilings. Each of these must be considered when estimating the heat loss of a building.

The following sample problem will help you to understand the importance of adding insulation to a building.

1. *Given*—A building constructed to provide the following thermal resistance (R) factors:
   a. Exterior shingles are R = 0.80
   b. Plywood sheathing is R = 0.75
   c. Building paper used is R = 0.04
   d. Wall structure has an R = 0.85
   e. Wall plaster has an R = 0.35
   f. Insulation is R = 11.0
2. *Find*—The total thermal resistance (R), the coefficient of heat transfer (U), and the watts (W) of heat loss both *with* and *without* the insulation.
3. *Solution* (without insulation):

$$\text{R} = \text{a} + \text{b} + \text{c} + \text{d} + \text{e}$$
$$= 0.80 + 0.75 + 0.04 + 0.85 + 0.35$$
$$= 2.79$$

$$\text{U} = \frac{1}{\text{R}}$$
$$= \frac{1}{2.79}$$
$$= 0.3584 \text{ Btu per ft}^2 \text{ per hour per } ^\circ\text{F}$$

$$\text{W} = \frac{\text{U}}{3.4}$$
$$= \frac{0.3584}{3.4}$$
$$= 0.1054 \text{ watts heat loss.}$$

4. *Solution* (with insulation):

$$\text{R} = \text{a} + \text{b} + \text{c} + \text{d} + \text{e} + \text{f}$$
$$= 0.80 + 0.75 + 0.04 + 0.85 + 0.35 + 11.0$$
$$= 13.79$$

$$\text{U} = \frac{1}{\text{R}}$$
$$= \frac{1}{13.79}$$
$$= 0.0725 \text{ Btu per ft}^2 \text{ per hour per } ^\circ\text{F}$$

$$\text{W} = \frac{\text{U}}{3.4}$$
$$= \frac{0.0725}{3.4}$$
$$= 0.0213 \text{ watts heat loss.}$$

You can see from the results of this problem that the adding of insulation into the walls of a building has a great effect upon heat loss. The insulation has a much greater effect in controlling heat loss than do the construction materials used for the building.

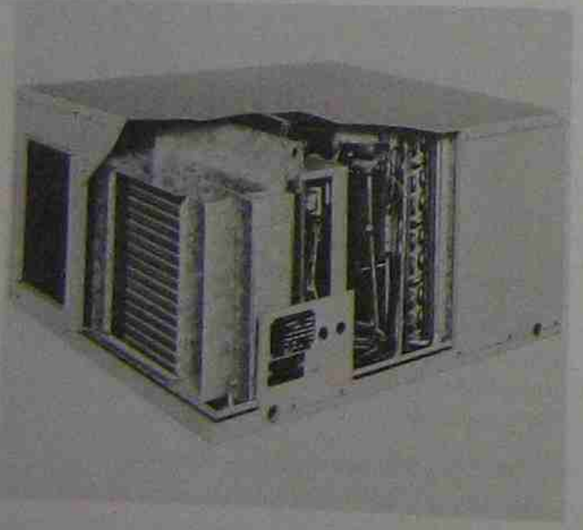
Electric Heating and Cooling Systems

Several types of electric heating systems are used today. Some common types are baseboard heaters, wall- or ceiling-mounted heaters and heat pumps. Most of

these systems use forced-air to circulate the heat. Some electric heaters have individual thermostats while others are connected to one central thermostat which controls the temperature in an entire building. The possibility of having temperature control in each room is an advantage of electric heating systems.

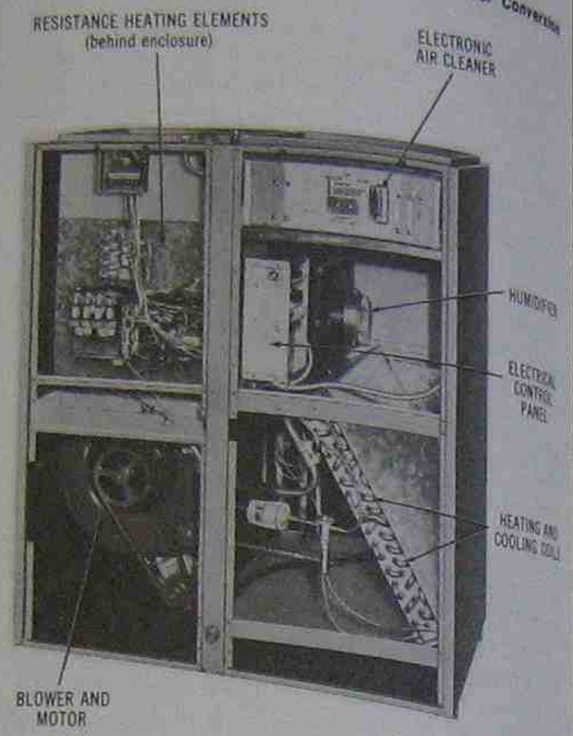
Heat Pumps—In recent years, the heat pump has become very popular as a combination heating and cooling unit for buildings. The heat pump is a heat-transfer unit. When the outside temperature is warm, the heat pump acts as an air-conditioning unit and transfers the indoor heat to the outside of the building. This operational cycle is reversed during cool outside temperatures. In the winter, the outdoor heat is transferred to the inside of the building. This process can take place during cold temperatures since there is always a certain amount of heat in the outside air, even at sub-zero temperatures. However, at the colder temperatures, there is less heat in the outside air.

Thus, heat pumps transfer heat rather than producing it. Since heat pumps do not produce heat, as resistive-heating units do, they are more economical in terms of energy conservation. Heating and cooling are reversible processes in the heat-pump unit; thus, the unit is self-contained. Fig. 12-9 shows a horizontally mounted heat-pump unit while Fig. 12-10 depicts a vertically mounted unit. The reversible feature of heat pumps reduces the space requirement for separate heating and cooling units. Another advantage is that the changeover from heating to cooling can be made automatically. This feature could be desirable during the spring and autumn seasons in the many areas where temperatures are very variable. In extremely cold areas, the heat pump can be supplemented by an auxiliary resistance-heating unit, such as shown in Fig. 12-11. This auxiliary unit will operate when the outside temperatures are very cold, and will be useful in maintaining the inside temperatures at a comfortable level. Air is circulated past these heating elements into the heat vents of the building.



Courtesy The Williamson Co.

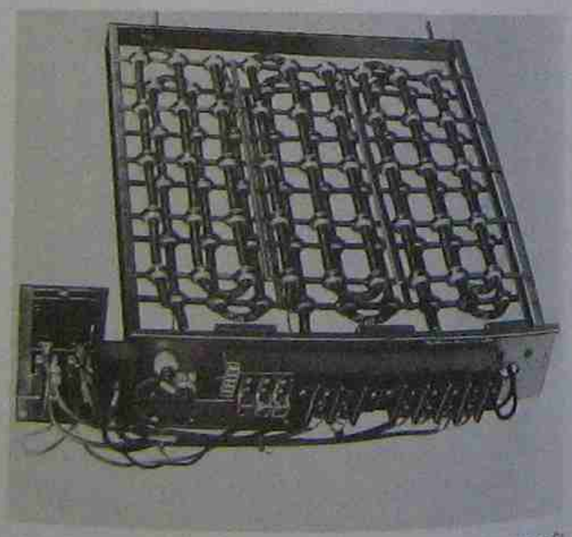
Fig. 12-9. A horizontally mounted heat-pump unit.



Courtesy The Williamson Co.

Fig. 12-10. A vertically mounted heat-pump unit.

Heat pumps are used for residential as well as commercial and industrial applications and are being



Courtesy The Williamson Co.

Fig. 12-11. A resistance-heating element for a heat pump.

used more extensively each year. Fig. 12-12 shows a simplified circuit arrangement of a heat pump in which a compressor takes a refrigerant from a low-temperature, low-pressure evaporator and converts it to a high temperature and a high pressure. The refrigerant is then delivered to a condenser much the same as a refrigerator functions.

Air-Conditioning Systems

The increased use of air-conditioning systems provides greater comfort in homes, industrial plants, and commercial facilities. Most air-conditioning units are for the purpose of controlling the inside temperature of buildings so as to make working and living conditions more comfortable. However, many units are used to cool the insides of various types of equipment. Both air temperature and the relative humidity are changed by air-conditioning units. In the design of air-conditioning systems, all heat-producing items must be considered. Body heat, electrical appliances, and lights represent some common sources of heat. The diffusion of heat takes place through floors, walls, ceilings, and the windows of buildings. A simplified diagram of a room air-conditioning unit is shown in Fig. 12-13.

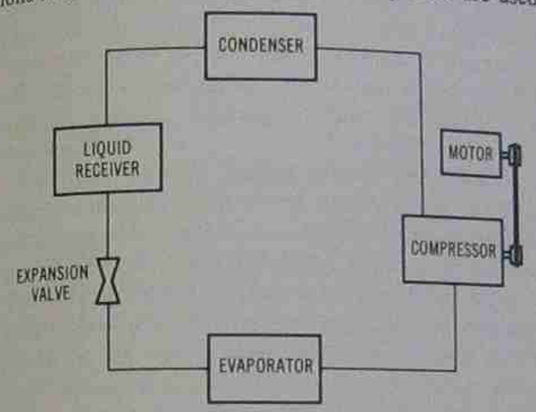


Fig. 12-12. A simplified heat-pump circuit diagram.

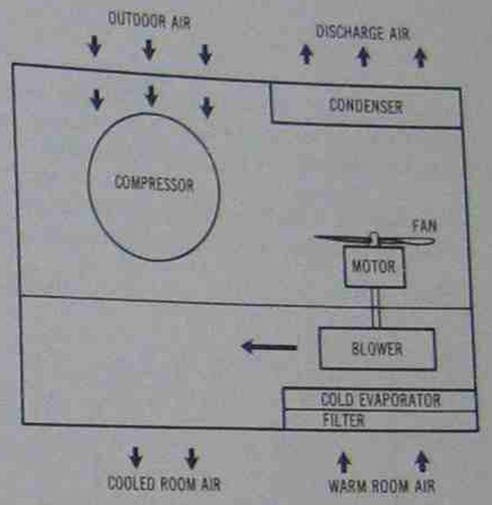


Fig. 12-13. A simplified diagram of a room air-conditioning unit.

PROBLEMS

1. A building has the following thermal resistance (R) factors.
   a. Exterior shingles have an $R = 0.75$
   b. Sheathing has an $R = 0.85$
   c. Building paper is $R = 0.06$
   d. Walls are $R = 0.80$
   e. Plaster on walls is $R = 0.30$

   Find the total thermal resistance (R), the coefficient of heat transfer (U), and the watts (W) of heat loss.

2. Find the R, U, and W for the building in Problem 1 after an insulation factor of $R = 13$ is added to the list.

CHAPTER 13

Lighting Systems

Electrical lighting systems are designed to create a comfortable and safe home or working environment. There are several types of lighting systems in use today. Among the most popular are incandescent, fluorescent, and mercury-vapor lights, and several special-purpose types of lighting. Lighting systems are one type of electrical *load*.

The three types of lighting systems discussed in this chapter constitute most of the lighting loads placed on electrical power systems. Incandescent, fluorescent, and vapor lights are used for many lighting applications. However, there are a few other specialized types of lighting that are also used. These include zirconium and xenon arc lights, glow lights, black lights, and infrared lights. The planning involved to obtain proper lighting is quite complex and may involve several types of lights.

CHARACTERISTICS OF LIGHT

In order to better understand lighting systems, you should know something about the basic characteristics of light. Light is a visible form of radiation that is actually a narrow band of frequencies along the vast electromagnetic spectrum. The electromagnetic spectrum, shown in Fig. 13-1, includes bands of frequencies for radio, television, radar, infrared radiation, visible light, ultraviolet light, x-rays, gamma rays, and various other frequencies. The different types of radiation, such as light, heat, radio waves, and x-rays, differ only with respect to their frequencies or wavelengths.

The human eye responds to electromagnetic waves in the *visible light* band of frequencies. Each color of light has a different frequency or wavelength. In order of increasing frequency (or decreasing wavelengths), the colors are red, orange, yellow, green, blue, and violet. The wavelengths of visible light are in the 400-millimicrometer (violet) to 700-millimicrometer (red) range. A micrometer (μm) is one millionth of a meter and a nanometer (nm) is 1×10^{-3} micrometer. Angstrom units (Å) are also used for light measurement. An angstrom unit is one-tenth of a nanometer. In order to avoid confusion, use the conversion chart given in Table 13-1.

Visible light ranges from 4000 Å to 7000 Å. The response of the human eye to visible light exhibits a

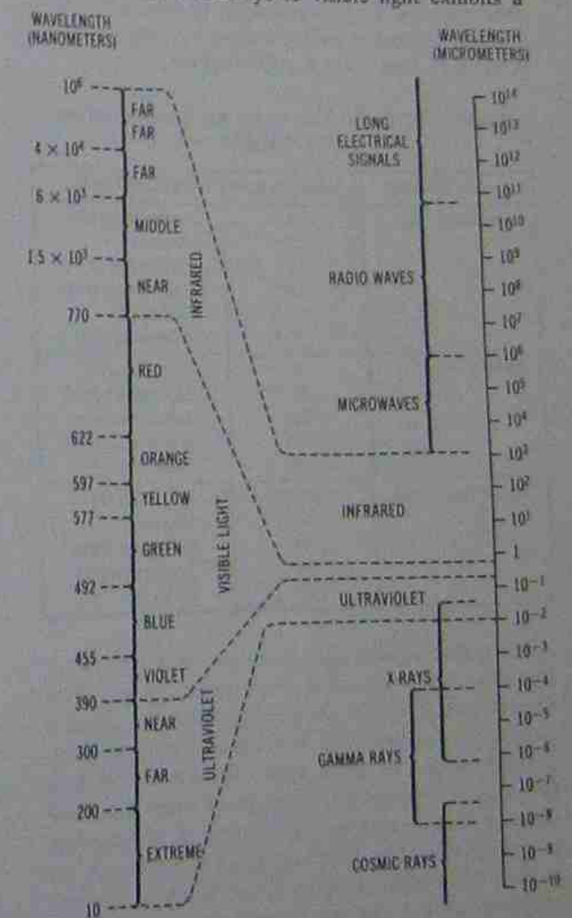


Fig. 13-1. The electromagnetic spectrum.

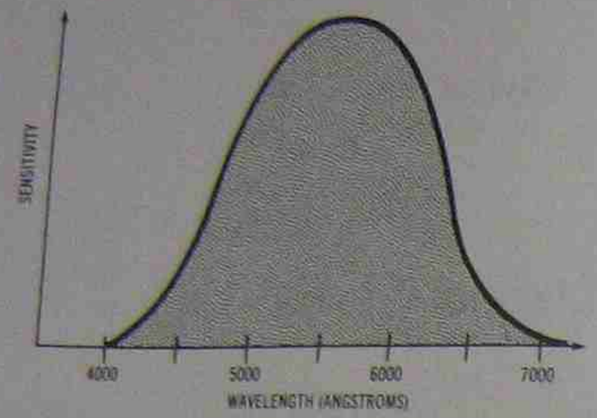


Fig. 13-2. Response of the human eye to visible light.

frequency selective characteristic, such as shown in Fig. 13-2. The greatest sensitivity is near 5500 Å. The poorest sensitivity is around 4000 Å on the lower wavelengths and 7000 Å on the higher wavelengths. Our eyes perceive various degrees of brightness due to their response to the wavelengths of light. The normal human eye cannot see a wavelength of less than 4000 Å or more than 7000 Å (400–700 nm).

Table 13-1. Conversion Chart for Electromagnetic Wavelengths

Known Quantity	Multiply by	Quantity To Find
Angstrom (Å)	10	Nanometer (nm)
	10^{4}	Micron
	10^{7}	Millimeter (mm)
	10^{8}	Centimeter (cm)
	10^{10}	Meter (m)
	10^{13}	Kilometer (km)
Micron	10^{-4}	Angstrom (Å)
	10^{-3}	Nanometer (nm)
	10^{3}	Millimeter (mm)
	10^{4}	Centimeter (cm)
	10^{6}	Meter (m)
Nanometer (nm)	10^{-7}	Angstrom (Å)
	10^{3}	Micron
	10^{6}	Millimeter (mm)
	10^{7}	Centimeter (cm)
	10^{9}	Meter (m)

When dealing with light, there are several characteristic terms which should be understood. The unit of luminous intensity is a standard light source called a *candela* or *candlepower*. The intensity of light is expressed in one of these units. The amount of light falling on a unit surface, all points of which are a unit distance from a uniform light source of one candela, is one *lumen*. The illumination of a surface is the number of lumens falling on it per unit area. The unit of illumination is the *lux* (lumens per square meter) or *footcandle* (lumens per square foot).

We see only light which is reflected. Reflected light is measured in candelas per square meter of surface (or footlamberts). The *reflection factor* is the percent of light reflected from a surface expressed as a decimal. Therefore, the light reflected from a surface is equal to the illumination of the surface times the reflection factor. The brightness of a surface which reflects one lumen per square foot is one *footlambert*.

Units of light measurement are given in both English and Systems International (metric) units. This can become somewhat confusing. The following list summarizes the most common terms used for light measurement.

Candela—Intensity of light.
Candela per square meter—Brightness of a surface.
Candlepower—See Candela.
Footcandle—See Lux.
Footlambert—See Candela per square meter.
Lumen—Amount of light falling on a surface.
Lux—Level of illumination of a surface (per unit area).

STREET LIGHTING

The lighting systems of today are highly reliable when compared to the systems that were installed many years ago. Earlier systems were either turned on and off manually or by timing devices that were regulated by the time of day rather than the natural light intensity. Some were controlled by electrical impulses that were transmitted on the power lines. Now, most systems are controlled by automatic photoelectric circuits. The lights which are now used to illuminate streets and highways have photoelectric controls. They operate during periods of darkness and are automatically turned off when natural light is present. These street lights are usually connected to existing 120/240-volt power distribution systems.

There are many types of street lights in use. The earliest types of street lights used were 200- to 1000-watt incandescent lamps. Now mercury- and sodium-vapor lamps are the primary types used. (Mercury lamps produce a white light and sodium lamps have a yellowish color.) Several different lamp designs and mounting fixture designs are used.

Several years ago, street lights were converted from incandescent lamps to mercury-vapor lamps. Now the trend in street lighting seems to be toward the use of sodium-vapor lights, and several areas of the country have converted to the use of sodium-vapor lamps. Sodium-vapor lights produce more illumination than a similar mercury-vapor light. They also require less electrical power to produce a specific amount of illumination. Thus, the ability of sodium-vapor lights to deliver more light with less power consumption makes them more economically attractive than mercury-vapor lights.

Incandescent Lighting

Incandescent lighting is a widely used method of lighting and it is used for many different applications. The construction of an incandescent lamp is shown in Fig. 13-3. This lamp is simple to install and maintain. The initial cost is low; however, incandescent lamps have a relatively low efficiency and a short life span.

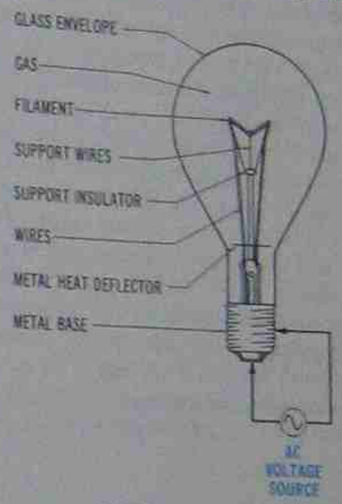
Incandescent lamps usually have a thin tungsten filament which is in the shape of a coiled wire. This filament is connected through the lamp base to a voltage source (usually 120 volts ac). When an electric current is passed through the filament, the temperature of the filament rises to between 3000° to 5000° Fahrenheit. At this temperature range, the tungsten produces a high-intensity white light. When the incandescent lamp is manufactured, the air is removed from the glass envelope to prevent the filament from burning; also, an inert gas is added.

Incandescent lamps are purely resistive devices and, thus, have a power factor of 1.0. As they deteriorate, their light output is reduced. Typically, at the time that an incandescent lamp burns out, its light output is less than 85% of its original output. A decrease in the voltage of the power system also reduces the light output. A 1% decrease in voltage will cause a 3% decrease in light output.

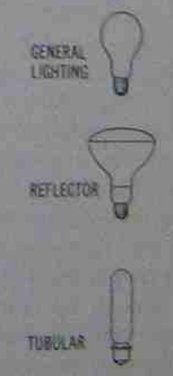
Fluorescent Lighting

Fluorescent lighting is used extensively today, particularly in industries and commercial buildings. Fluorescent lamps are tubular bulbs with a filament at each end. There is no electrical connection between the two filaments. The operating principle of the fluorescent lamp is shown in Fig. 13-4. The tube is filled with mercury vapor; thus, when an electrical current flows through the two filaments, a continuous arc is formed between them by the mercury vapor. High-velocity electrons passing between the filaments collide with the mercury atoms, producing an ultraviolet radiation. The inside of the tube has a phosphor coating which reacts with the ultraviolet radiation to produce visible light.

The circuit for a fluorescent light is shown in Fig. 13-5. Note that a thermal starter, which is basically a bimetallic strip and a heater, is connected in series with the filaments. The bimetallic strip remains closed long enough for the filaments to heat and vaporize the mercury in the tube. The bimetallic switch will, then, bend and open due to the heat produced by current flow through the heater. The filament circuit is now opened. A capacitor is connected across the bimetallic switch to reduce contact sparking. Once the contacts of the starter open, a high voltage is momentarily placed between the filaments of the lamp due to the



(A) Construction.



(B) Types.

Fig. 13-3. The incandescent lamp.

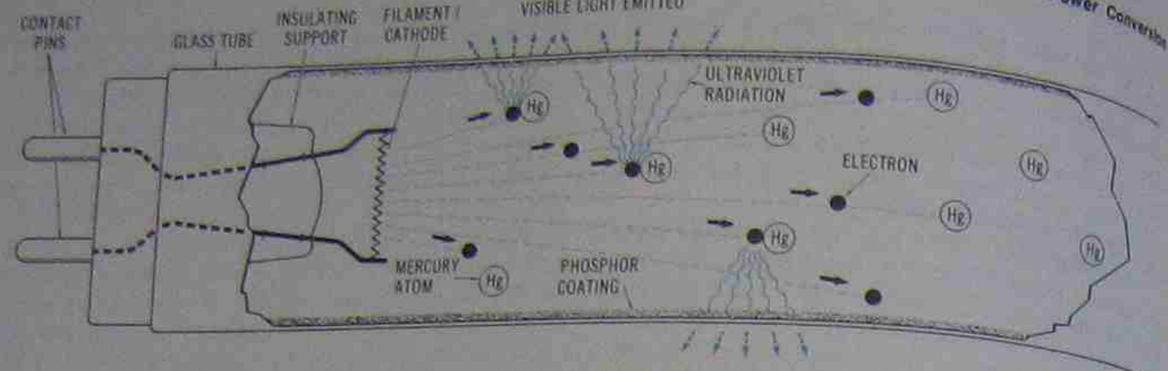


Fig. 13-4. Operating principle of a fluorescent lamp.

action of the inductive ballast coil. The ballast coil has many turns of small-diameter wire and, thus, produces a high counterelectromotive force when the contacts of the starter separate. This effect is sometimes called "inductive kickback." The high voltage across the filaments causes the mercury to ionize and initiates a flow of current through the tube. There are several other methods used to start fluorescent lights; however, this method illustrates the basic operating principle.

Fluorescent lights produce more light per watt than incandescent lights; therefore, they are cheaper to operate. Since the illumination is produced by a long tube, there is also less glare. The light produced by fluorescent bulbs is very similar to natural daylight. The light is whiter and the operating temperature is much less with fluorescent lights. Various sizes and shapes of fluorescent lights are available. The bulb sizes are expressed in eighths of an inch with the common sizes being T-12 and T-8. (A T-12 bulb is 1½ inch or 38.1 mm in diameter.) Common lengths are 24, 48, 72, and 96 inches (0.61, 1.22, 1.83, and 2.44 meters, respectively).

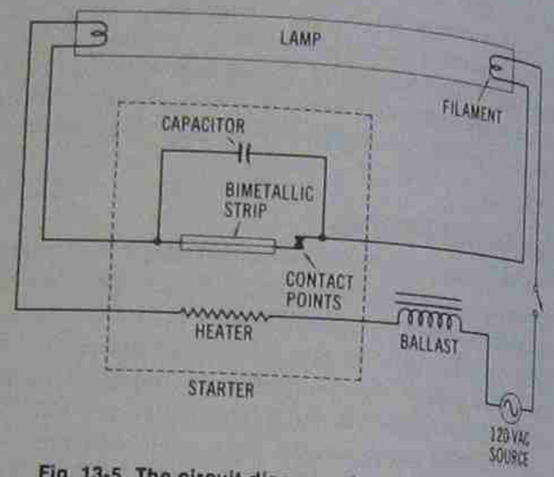


Fig. 13-5. The circuit diagram of a fluorescent lamp.

Vapor Lighting

Another popular form of lighting is the vapor type. The mercury-vapor light is one of the most common types of vapor lights. Another common type is the sodium-vapor light. These lights are filled with a gas which produces a characteristic color. For instance, mercury vapor produces a greenish-blue light and argon a bluish-white light. Gases may be mixed to produce various color combinations for vapor lighting. This is often done with signs used for advertising.

A mercury-vapor lamp is shown in Fig. 13-6. It consists of two tubes with an arc tube placed inside an outer bulb. The inner tube contains mercury. When a voltage is applied between the starting probe and an electrode, an arc is started between them. The arc current is limited by a series resistor; however, the current is enough to cause the mercury in the inner tube to ionize. Once the mercury has ionized, an intense greenish-blue light is produced. Mercury-vapor lights are compact, long-lasting, and easy to maintain. They are used to provide a high-intensity light output. At low voltages, mercury is slow to vaporize, so these lamps require a long starting time (sometimes 4 to 8 minutes). Mercury-vapor lights can also be used for outdoor lighting.

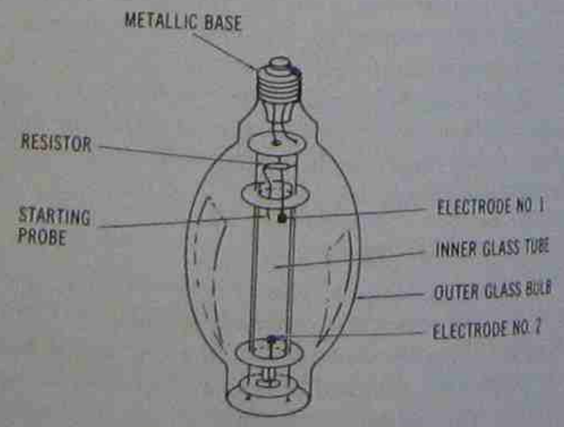


Fig. 13-6. A mercury-vapor lamp.

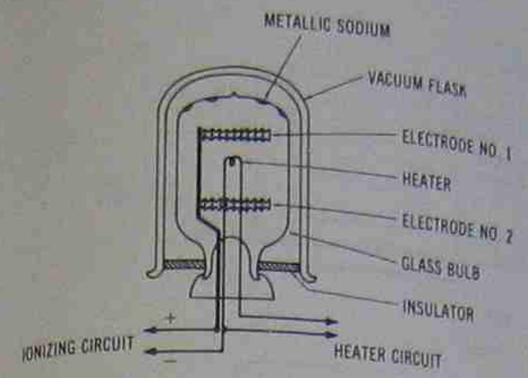


Fig. 13-7. A sodium-vapor lamp.

The sodium-vapor light, shown in Fig. 13-7, is popular for outdoor lighting and for highway lighting. This lamp contains some low-pressure neon gas and some sodium. When an electric current is passed through the heater, electrons are given off. The ionizing circuit causes a positive charge to be placed on the electrodes. As electrons pass from the heater to the positive electrodes, the neon gas is ionized. The ionization of the neon gas produces enough heat to cause the sodium to ionize. A yellowish light is produced by the sodium vapor. The sodium-vapor light can produce about three times the candlepower per watt as that of an incandescent light.

ELECTRICAL LIGHTING CIRCUITS

There are several types of electrical circuits that are used for electrical lighting control. We will study some of the circuits used for incandescent and fluorescent lighting systems. Electrical lighting circuits for different areas of a building must be wired properly. Some lighting fixtures are controlled from one point by one switch while other fixtures may be controlled from two or more points by a switch at each point.

Incandescent lighting circuits are a typical type of branch circuits. The most common type of incandescent lighting circuit is a 120-volt branch that extends from a power distribution panel to a light fixture or fixtures in some area of a building. The path for the electrical distribution is controlled by one or more switches that are usually placed in small metal or plastic enclosures inside a wall. These switches are then covered by rectangular plastic plates to prevent possible shock hazards.

Switches are always placed in a wiring circuit so that they can open or close a *hot* wire. This hot wire distributes electrical power to the lighting fixtures which the switches control. These switches are referred to as "T-rated" switches. They are designed to handle the high instantaneous current drawn by lights when they are turned on or off. A switch which accomplishes

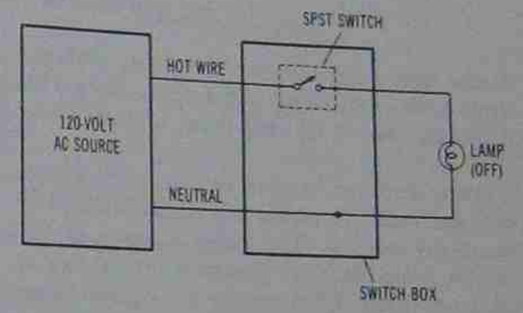


Fig. 13-8. Schematic diagram for the control of a light from one location.

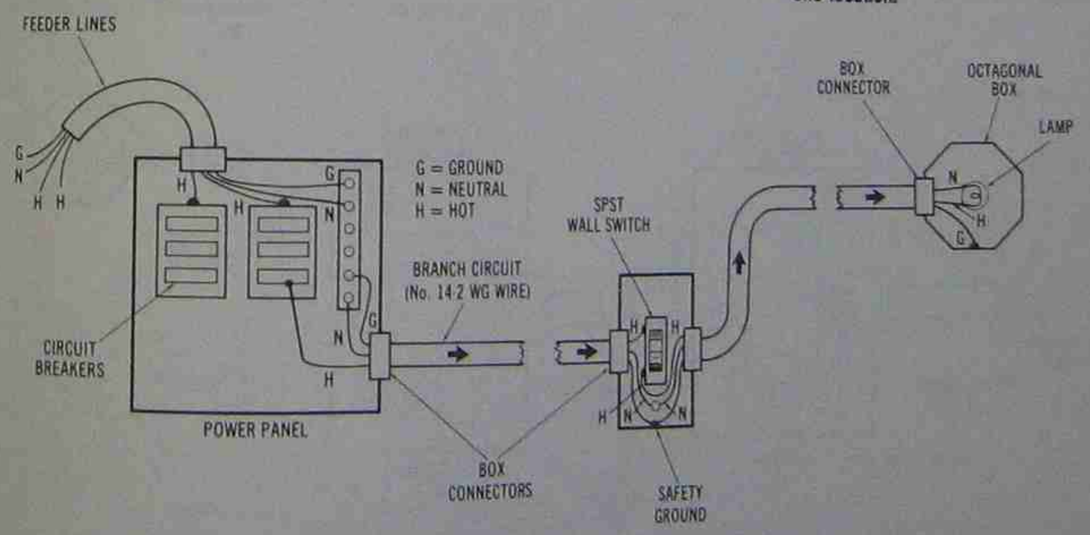
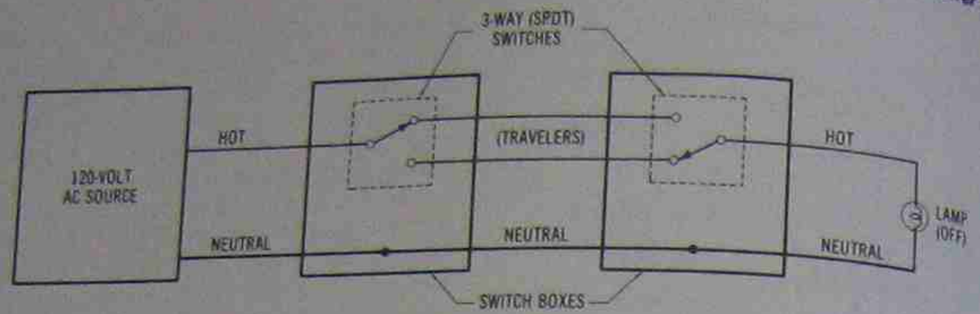
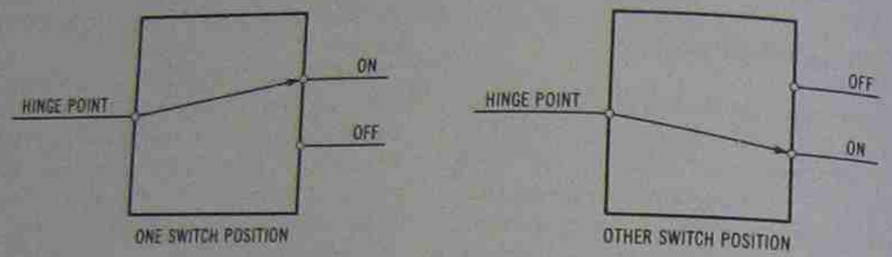


Fig. 13-9. Pictorial view of diagram given in Fig. 13-8.

LIBRARY



(A) Schematic diagram.



(B) Positions of three-way switches.

Fig. 13-10. Circuit for controlling a light from two locations.

control from a single location is a simple single-pole single-throw (spst) switch, such as shown in Fig. 13-8. A pictorial view of the same circuit is shown in Fig. 13-9.

Control from two locations, such as near the kitchen door and inside the garage door, is accomplished by two 3-way switches. This circuit is shown in Fig. 13-10A, while Fig. 13-11 presents a pictorial view of the same circuit. When control of a lighting fixture from more than two points is desired, two 3-way switches and one or more 4-way switches are used. For instance, control of one light from five points could be accomplished by using a combination of two 3-way switches and three 4-way switches. Fig. 13-12 shows a circuit for controlling a light from three locations. The 3-way switches are always connected to the power panel and to the light fixture, with the 4-way switch between them. Using 3-way and 4-way switch combinations, it is possible to achieve control of a light from any number of points.

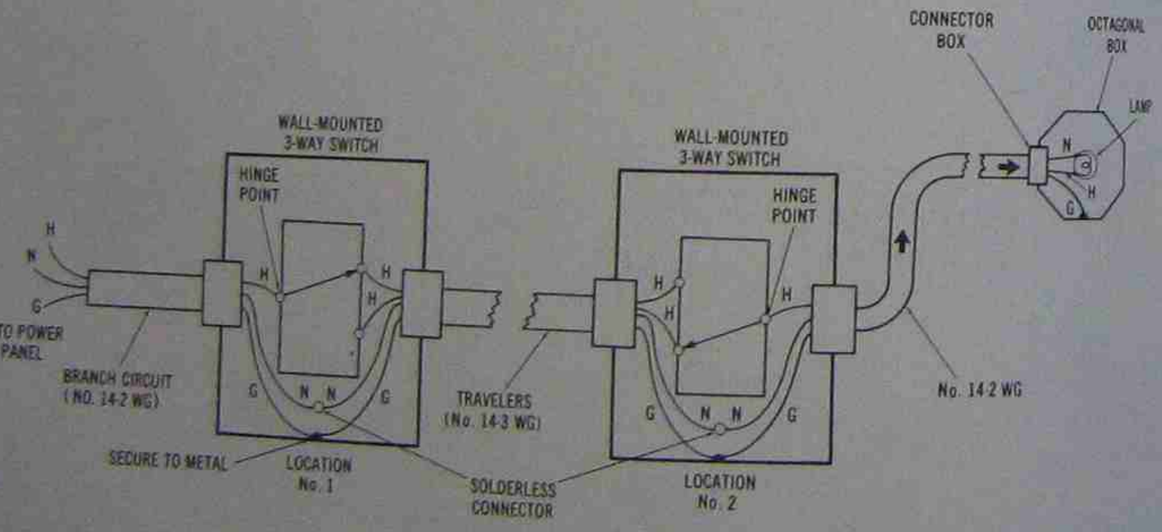
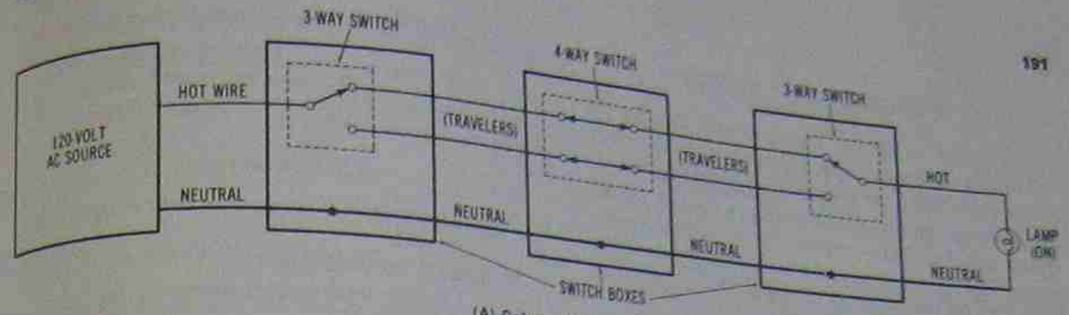
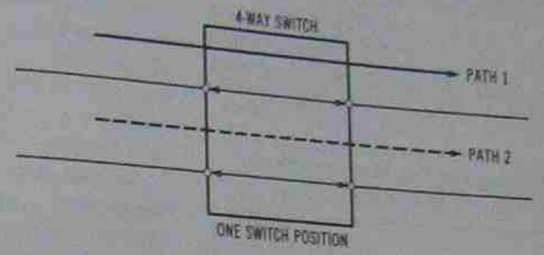


Fig. 13-11. Pictorial view of circuit shown in Fig. 13-10.



(A) Schematic diagram.



(B) Positions of the 4-way switch.

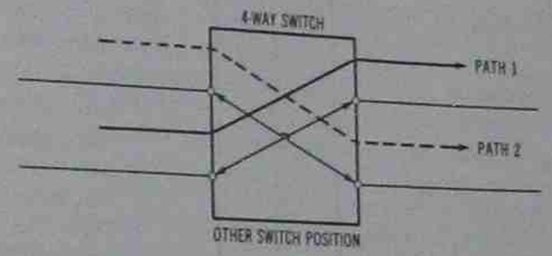


Fig. 13-12. Circuit for controlling a light from three locations.

Each lighting-control circuit requires an entirely different type of switching combination to adequately accomplish control of a lighting fixture. These circuits are usually wired into buildings during construction to provide the type of lighting control desired for each room. You should study the diagrams of Figs. 13-8 through 13-13 to fully understand how these lighting circuits operate.

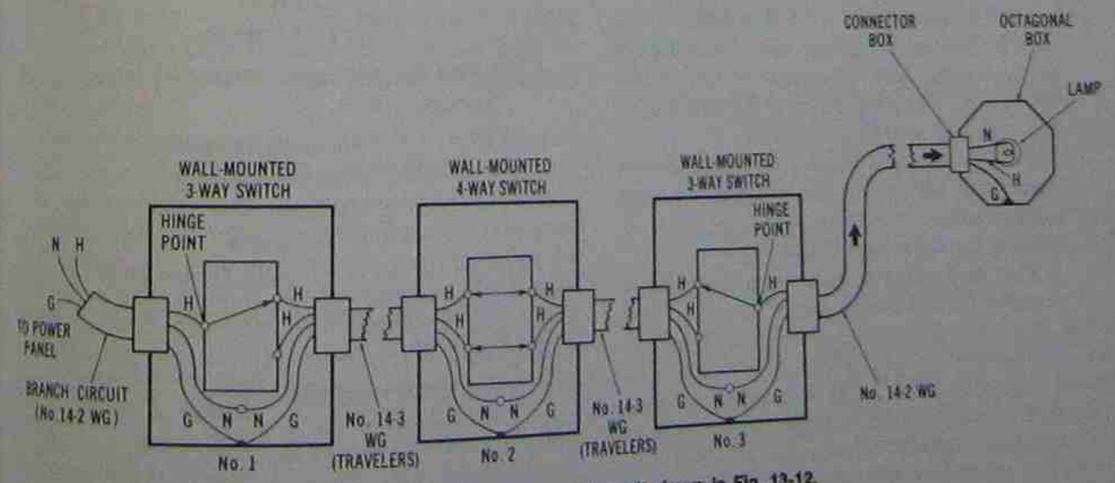


Fig. 13-13. Pictorial view of circuit shown in Fig. 13-12.

BRANCH-CIRCUIT DESIGN

The design of lighting branch circuits involves the calculation of the maximum current that can be drawn by the lights which are connected to the branch circuit. Many times, particularly in homes, a lighting branch circuit also has duplex receptacles for portable appliances. This causes the exact current calculation to be more difficult, since not all the lights or the appliances will be in use at the same time.

The National Electrical Code (NEC) specifies that there should be at least one branch circuit for each 500 square foot of lighting area. The NEC further specifies a minimum requirement of lighting for various types of buildings. Table 13-2 lists the number of watts of light per square foot required in some buildings.

Table 13-2. Building Lighting Requirements in Wattage per Square Foot

Type of Building	Watts
Armories and auditoriums	1
Banks	2
Churches	1
Dwellings (other than hotels)	3
Garages (for commercial storage)	½
Hospitals	2
Hotels and motels	2
Industrial or commercial buildings	2
Office buildings	5
Restaurants	2
Schools	3
Stores (grocery)	3
Warehouses (storage)	¼

The solution of a typical branch-circuit lighting problem follows.

1. *Given*—A room in a commercial building is 70 feet × 120 feet (21.34 × 36.58 meters). It will use 125 fluorescent lighting units which draw 3 amperes each. Also, 20-ampere branch circuits will be used. The power factor of the units is 0.75. The operating voltage is 120 volts.
2. *Find*—The minimum number of branch circuits needed and the total power requirement for the lighting units.
3. *Solution* for the branch circuits:
   a. Find the number of units which should be installed on each branch circuit.

$$\text{Units} = \frac{\text{Branch current}}{\text{Load current}}$$
$$= \frac{20 \text{ amperes}}{3 \text{ amperes}}$$
$$= 6.67 \text{ units (round off at 6)}$$

   b. Find the number of branch circuits needed.

$$\text{Circuits} = \frac{\text{Lighting units}}{\text{No. units per branch circuit}}$$
$$= \frac{125}{6}$$
$$= 20.8 \text{ (round up to 21)}$$

   Twenty-one 20-ampere branch circuits will be needed.

4. *Solution* for total power:
   a. Find the total current drawn by the lights.

$$I = 125 \text{ units} \times 3 \text{ amperes}$$
$$= 375 \text{ amperes}$$

   b. Calculate the total power.

$$P = V \times I \times pf$$
$$= 120 \times 375 \times 0.75$$
$$= 33{,}750 \text{ watts (33.75 kW)}$$

An even more common type of branch-circuit lighting problem is given in the following discussion. The problem begins with the minimum amount of light required in a room. The number of branch circuits that are required must be determined.

1. *Given*—A large room in an industry needs to have 40,000 watts of incandescent lighting. It was decided that 120-volt 20-ampere branch circuits would be used. The lights will use 200-watt bulbs.
2. *Find*—The number of branch circuits required for the lighting.
3. *Solution:*
   a. Find the amount of current each lamp will draw.

$$I = \frac{P}{V}$$
$$= \frac{200 \text{ watts}}{120 \text{ volts}}$$
$$= 1.67 \text{ amperes}$$

   b. Find the maximum number of lamps in each branch circuit.

$$\text{Lamps} = \frac{\text{Amperage of circuit}}{\text{Amperage of lamps}}$$
$$= \frac{20 \text{ amperes}}{1.67 \text{ amperes}}$$
$$= 11.97 \text{ lamps (round off to 11)}$$

   c. Find the total number of bulbs (lamps) needed.

$$\text{Bulbs required} = \frac{\text{Wattage of room}}{\text{Wattage of bulbs}}$$
$$= \frac{40{,}000 \text{ watts}}{200 \text{ watts}}$$
$$= 200 \text{ bulbs required}$$

   d. Find the minimum number of branch circuits needed.

$$\text{Branch circuits} = \frac{\text{Total bulbs required}}{\text{Number bulbs per circuit}}$$
$$= \frac{200}{11}$$
$$= 18.18 \text{ (round up to 19)}$$

Nineteen branch circuits will be needed.

It should be pointed out that in these problems, we determined the *minimum* number of branch circuits. Some room for flexibility should be provided for each branch circuit. This can be done by designing the circuit to handle only 16 amperes (80%) rather than 20 amperes. Also, room should be provided on the power distribution panel to allow connecting some additional lighting branch circuits. This will allow additional loads to be connected at a later time.

LIGHTING FIXTURE DESIGN

Lighting fixtures are the devices which are used to hold lamps in place. They are commonly referred to as *luminaires*. Luminaires are used to *efficiently* transfer light from its source to a work surface. The proper designing of luminaires allows a more efficient transfer of light. It is important to keep in mind that *light intensity varies inversely as the square of the distance from the light source*. Thus, if the distance is doubled, the light intensity would be reduced four times.

Many factors must be considered in determining the amount of light which is transferred from a light bulb to a work surface. Some light is absorbed by the walls and by the light fixture itself; thus, not all light is efficiently transferred. The manufacturers of lighting systems develop charts that are used to predict the amount of light which will be transferred to a work surface. These charts consider the necessary variables for making a prediction of the quantity of light falling onto a surface.

Each luminaire has a rating that is referred to as its *coefficient of utilization*. The coefficient of utilization is a factor which expresses the percentage of light output which will be transferred from a lamp to a work area. The coefficient of a luminaire is determined by laboratory tests made by the manufacturer. These coefficiency charts also take into consideration the light absorption characteristics of walls, ceilings, and floors when determining the coefficient of utilization of a luminaire.

Another factor used for determining the coefficient of utilization is called the *room ratio*. Room ratio is very simply determined by the formula:

$$\text{Room Ratio} = \frac{W \times L}{H\,(W + L)}$$

where,
W is the room width in feet,
L is the room length in feet,
H is the distance in feet from the light source to the work surface.

Note: Work surfaces are considered to be 2.5 feet (0.76 meter) from the floor, unless otherwise specified.

FACTORS IN DETERMINING LIGHT OUTPUT

There are several other factors which must be considered in determining the amount of light transferred from a light source to a work surface. We know for instance that the age of a lamp has an effect on its light output. Lamp manufacturers determine a *depreciation factor* or *maintenance factor* for luminaires. This factor expresses the percentage of light output available from a light source. A depreciation factor of 0.75 means that in the daily use of a light source, only 75% of the actual light output is available for transfer to the work surface. The depreciation factor is an average value. It considers the reduction of light output with age and the accumulation of dust and dirt on the luminaires. Some collect dust more easily than others.

The following problem shows the effect of the coefficient of utilization (CU) and the depreciation factor (DF) on the light output transferred to a work surface.

1. *Given*—A lighting system for a building has 16 luminaires. Each luminaire has two fluorescent lamps. Each lamp has a light output of 3000 lumens. The CU and DF found in the chart developed by the manufacturer are 0.45 and 0.90, respectively.
2. *Find*—The total light output from the lighting system.
3. *Solution:*
   a. Find the total light output from the lamps:
   3000 lumens per lamp × 16 luminaires × 2 lamps per luminaire = 96,000 lumens
   b. Find the total light output:

$$\text{Light Output} = \text{Total Lumens} \times \text{CU} \times \text{DF}$$
$$= 96{,}000 \times 0.45 \times 0.90$$
$$= 38{,}880 \text{ lumens}$$

The distribution of light output onto work surfaces must also be considered. The coefficient of utilization and the depreciation factor are used to find the total light output of a lighting system. A greater light output is required for larger areas. The light output to a work surface is expressed as lumens per square foot or foot-

candles. A light meter is used to measure the quantity of light which reaches a surface.

The following two formulas are useful for finding the required lumens for a work area or the light output available from a particular lighting system:

$$\text{Total lumens} = \frac{\text{Desired footcandles} \times \text{Room area in ft}^2}{\text{CU} \times \text{DF}}$$

and

$$\text{Footcandles available} = \frac{\text{Total lumens} \times \text{CU} \times \text{DF}}{\text{Room area in feet}^2}$$

PROBLEMS

1. A storage room is 50 feet × 100 feet (15.2 × 30.5 meters). It will use 100 fluorescent lighting units which will each draw 2.5 amperes of current. Only 20-ampere 120-volt branch circuits are to be used. The power factor of the lighting system is 0.80. Find the minimum number of branch circuits needed and the total power required by the lighting units.

2. A room requires at least 25.5 kW of incandescent lighting. Only 120-volt 20-ampere branch circuits will be used. Each lamp unit is rated at 150 watts. Find the number of branch circuits required for lighting this room.

3. What is the room ratio of a 12-foot × 15-foot (3.66- × 4.57-meter) room?

4. A lighting system has 12 luminaries with two fluorescent bulbs mounted on each one. Each lamp has an output of 2500 lumens. The CU and DF are 0.50 and 0.85, respectively. Find the total light output from this system.

5. In what portion of the electromagnetic spectrum would each of the following wavelengths be?
   a. 2 meters
   b. 10^{-6} meters
   c. 10^{6} meters
   d. 10^{10} meters
   e. 400 nanometers
   f. 8×10^{3} nanometers
   g. 500 nanometers
   h. 4×10^{3} nanometers

6. What colors of visible light are produced by the following wavelengths?
   a. 750 nanometers
   b. 450 nanometers
   c. 650 nanometers
   d. 600 nanometers
   e. 500 nanometers
   f. 690 nanometers

7. Convert each of the wavelengths given in Problem 6 to angstroms.

CHAPTER 14

Mechanical Power-Conversion Systems

Another broad category of electrical loads includes those devices that convert electrical energy into mechanical energy. Electric motors fall into this category of load devices. They are mechanical power-conversion systems. There are many types of motors used today. The electrical motor load is the major power-consuming load of electrical power systems. Motors of various sizes are used for purposes that range from large industrial machine operation to the small motors that are used to power blenders and mixers in the home.

BASIC MOTOR PRINCIPLES

The function of a motor is to convert electrical energy into mechanical energy in the form of a rotary motion. To produce a rotary motion, a motor must have an electrical power input. Recall from Chapter 5 that generator action is brought about due to a magnetic field, a set of conductors within the magnetic field, and relative motion between the two. Motion is similarly produced in a motor due to the interaction of a magnetic field and a set of conductors.

All motors, regardless of whether they operate from an ac or a dc power line, have several basic characteristics in common. Their basic parts include (1) a stator, which is the frame and other stationary components; (2) a rotor, which is the rotating shaft and its associated parts; and (3) auxiliary equipment, such as a brush/commutator assembly for dc motors and a starting circuit for single-phase ac motors. The basic parts of a dc motor are shown in Fig. 14-1. A simple dc motor is constructed in the same way as a dc generator. Their basic parts are the same. Direct-current generators were discussed in Chapter 5.

The motor principle is illustrated in Fig. 14-2. In Fig. 14-2A, no current is flowing through the conductors due to the position of the brushes in relation to the commutator. During this condition, no motion is produced. When current flows through the conductor, a circular magnetic field is developed around the conductor. The direction of the current flow determines the direction of the circular magnetic fields, as shown in the cross-sectional diagram of Fig. 14-2C.

When current flows through the conductors within the main magnetic field, this field interacts with the main field. The interaction of these two magnetic fields results in motion being produced. The circular magnetic field around the conductors causes a compression of the main magnetic flux at points A and B in Fig. 14-2B. This compression causes the magnetic field to produce a reaction in the opposite direction of the compression. Therefore, motion is produced away from points A and B. In actual motor operation, a rotary motion in a clockwise direction would be produced. If we wished to change the direction of rotation, we would merely have to reverse the direction of the current flow through the conductors.

The rotating effect produced by the interaction of two magnetic fields is called *torque* or *motor action*. The torque produced by a motor depends on the strength of the main magnetic field and the amount of current flowing through the conductors. As the mag-

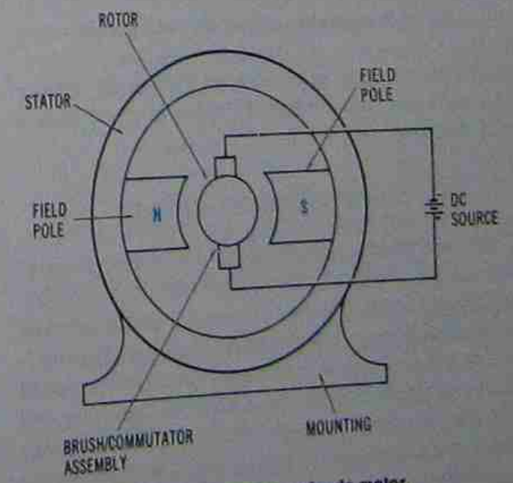
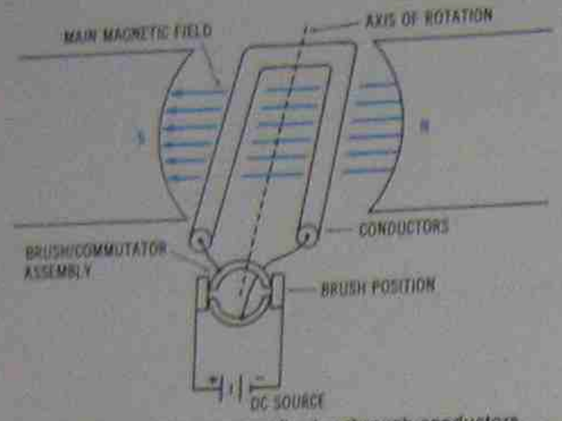
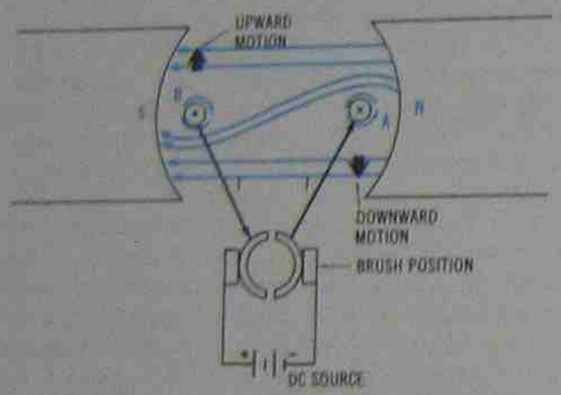


Fig. 14-1. Basic parts of a dc motor.



(A) Condition with no current flowing through conductors.



(B) Condition with current flowing through conductors.

(C) Direction of current flow through conductors determines direction of magnetic field around conductors.

Fig. 14-2. Illustration of the basic motor principle.

netic field strength or the current through the conductors increases, the amount of torque or rotary motion will increase also.

DIRECT-CURRENT MOTORS

Motors which operate from direct-current power sources are often used in industry when speed control is desirable. Direct-current motors are almost identical in construction to dc generators. They are also classified in a similar manner as series, shunt, or compound machines depending on the method of connecting the armature and field windings. The permanent-magnet dc motor is another type of motor that is used for certain applications.

DC Motor Characteristics

The operational characteristics of all dc motors may be generalized by referring to Fig. 14-3. Most electric motors exhibit characteristics similar to those shown in the block diagram. When discussing dc motor characteristics, we should be familiar with the terms load, *speed*, *counterelectromotive force* (cemf), *armature current*, and *torque*. The amount of mechanical load applied to the shaft of a motor determines its operational characteristics. As the mechanical load is increased, the speed of a motor tends to decrease. As speed decreases, the voltage induced into the conductors of the motor due to generator action (cemf) decreases. The generated voltage or counterelectromotive force depends upon the number of rotating conductors and the speed of rotation. Therefore, as speed of rotation decreases, so does the cemf.

The counterelectromotive force generated by a dc motor is in opposition to the supply voltage. Therefore, the actual working voltage of a dc motor may be expressed as:

$$V_T = V_C + I_A R_A$$

where,

V_T is the terminal voltage of the motor in volts,
V_C is the cemf generated by the motor in volts,
$I_A R_A$ is the voltage drop across the armature of the motor in volts.

Since the cemf is in opposition to the supply voltage, the actual working voltage of a motor will increase as the cemf decreases. Due to an increase in working voltage, more current will flow through the armature conductors which are connected to the dc power supply. Since torque is directly proportional to armature current, the torque will increase as the armature current increases.

To briefly discuss the opposite situation, if the mechanical load connected to the shaft of a motor decreases, the speed of the motor would tend to increase. An increase in speed causes an increase in generated voltage. Since cemf is in opposition to the supply voltage, as cemf increases, the armature current decreases. A decrease in armature current causes a decrease in torque. We can see that torque varies with changes in load, but we need to consider each of the steps involved to understand dc motor operation. As the load on a motor is increased, its torque also increases to try to meet the increased load requirement. However, the current drawn by a motor also increases when load is increased.

The presence of a cemf to oppose armature current is very important in motor operation. The lack of any cemf when a motor is being started explains why motors

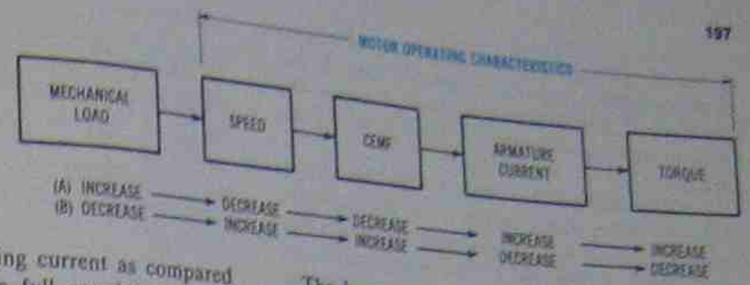


Fig. 14-3. Operational characteristics of dc motors.

draw a very large initial starting current as compared to their running current when full speed is reached. Maximum armature current flows when there is no cemf. As cemf increases, armature current decreases. Thus, resistances in series with the armature circuit are often used to compensate for the lack of cemf and to reduce the starting current of a motor. After a motor has reached full speed, these resistances may be bypassed by automatic or manual switching systems in order to allow the motor to produce maximum torque. Keep in mind that the armature current, which directly affects torque, can be expressed as:

$$I_A = \frac{V_T - V_C}{R_A}$$

where,

I_A is the armature current in amperes,
V_T is the terminal voltage of the motor in volts,
V_C is the cemf generated by the motor in volts,
R_A is the armature resistance in ohms.

In determining the functional characteristics of a motor, the torque developed can be expressed as:

$$T = K\Phi I_A$$

where,

T is the torque in foot-pounds,
K is a constant based on physical characteristics (conductor size, frame size, etc.),
Φ is the quantity of magnetic flux between poles,
I_A is the armature current in amperes.

Torque can be measured by several types of motor analysis equipment.

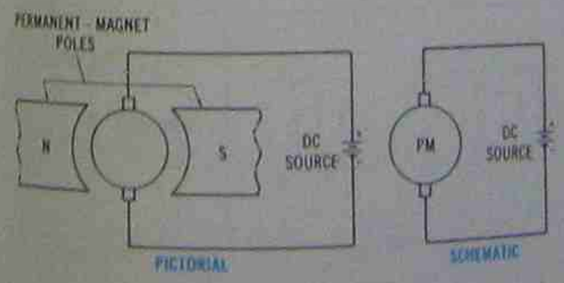


Fig. 14-4. Permanent-magnet dc motor.

The horsepower rating of a motor is based on the amount of torque produced at the rated full-load values. Horsepower, which is the usual method of rating motors, can be expressed mathematically as:

$$hp = \frac{2\pi NT}{33{,}000} = \frac{NT}{5252}$$

where,

hp is the horsepower rating,
2π is a constant,
N is the speed of the motor in revolutions per minute (rpm),
T is the torque developed by the motor in foot-pounds.

Another dc motor characteristic that we should discuss is armature reaction. Armature reaction was discussed in relation to dc generators in Chapter 5. This effect distorts the main magnetic field in dc motors as well as in dc generators. Similarly, the brushes of a dc motor can be shifted to counteract the effect of armature reaction. However, interpoles are ordinarily used to control armature reaction in dc motors.

The most desirable characteristic of dc motors is their speed-control capability. By varying the applied dc voltage with a rheostat, speed can be varied from zero to the maximum rpm of the motor. Some types of dc motors have more desirable speed characteristics than others. For this reason, we can determine the comparative speed regulation for different types of motors. Speed regulation is expressed as:

$$\%R = \frac{S_{NL} - S_{FL}}{S_{FL}} \times 100$$

where,

%R is the percentage of speed regulation,
S_{NL} is the no-load speed in rpm,
S_{FL} is the rated full-load speed in rpm.

Good speed regulation (low %R) results when a motor has nearly constant speeds under varying load situations.

Types of DC Motors

The types of commercially available dc motors basically fall into four categories: (1) permanent-magnet

dc motors, (2) series-wound dc motors, (3) shunt-wound dc motors, and (4) compound-wound dc motors. Each of these motors has different characteristics due to its basic circuit arrangement and physical properties.

Permanent-Magnet DC Motors—The permanent-magnet dc motor, shown in Fig. 14-4, is constructed in the same manner as its dc generator counterpart that was discussed in Chapter 5. The permanent-magnet motor is used for low-torque applications. When this type of motor is used, the dc power supply is connected directly to the armature conductors through the brush/commutator assembly. The magnetic field is produced by permanent magnets mounted on the stator.

This type of motor ordinarily uses either alnico or ceramic permanent magnets rather than field coils. The alnico magnets are used with high-horsepower applications. Ceramic magnets are ordinarily used for low-horsepower slow-speed motors. Ceramic magnets are highly resistant to demagnetization, yet they are relatively low in magnetic-flux level. The magnets are usually mounted in the motor frame and, then, magnetized prior to the insertion of the armature.

The permanent-magnet motor has several advantages over conventional types of dc motors. One advantage is a reduced operational cost. The speed characteristics of the permanent-magnet motor are similar to the shunt-wound dc motor. The direction of rotation of a permanent-magnet motor can be reversed by reversing the two power lines.

Series-Wound DC Motors—The manner in which the armature and field circuits of a dc motor are connected determines its basic characteristics. Each of the types of dc motors are similar in construction to the type of dc generator that corresponds to it. The only difference, in most cases, is that the generator acts as a voltage source while the motor functions as a mechanical power-conversion device.

The series-wound motor, shown in Fig. 14-5, has the armature and field circuits connected in a series arrangement. There is only one path for current to flow from the dc voltage source. Therefore, the field is wound of relatively few turns of large-diameter wire, giving the field a low resistance. Changes in load applied to the motor shaft causes changes in the current through the field. If the mechanical load increases, the current also increases. The increased current creates a stronger magnetic field. The speed of a series motor varies from very fast at no load to very low at heavy loads. Since large currents may flow through the low-resistance field, the series motor produces a high torque output. Series motors are used where heavy loads must be moved and speed regulation is not important. A typical application is for automobile starter motors.

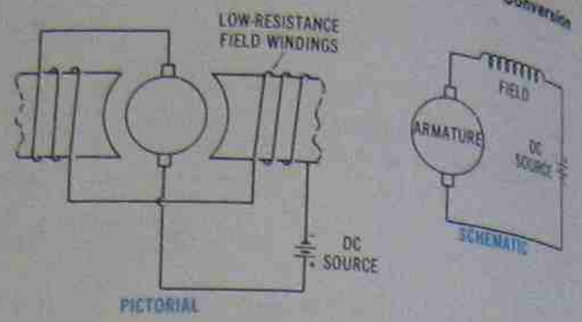


Fig. 14-5. Series-wound dc motor.

Shunt-Wound DC Motors—Shunt-wound dc motors are more commonly used than any other type of dc motor. As shown in Fig. 14-6, the shunt-wound dc motor has field coils connected in parallel with its armature. This type of dc motor has field coils which are wound of many turns of small-diameter wire and have a relatively high resistance. Since the field is a high-resistant parallel path of the circuit of the shunt motor, a small amount of current flows through the field. A strong electromagnetic field is produced due to the many turns of wire which form the field windings.

A large majority (about 95%) of the current drawn by the shunt motor flows in the armature circuit. Since the field current has little effect on the strength of the field, motor speed is not affected appreciably by variations in load current. The relationship of the currents which flow through a dc shunt motor is as follows:

$$I_T = I_A + I_F$$

where,

I_T is the total current drawn from the power source,
I_A is the armature current,
I_F is the field current.

The field current may be varied by placing a variable resistance in series with the field windings. Since the current in the field circuit is low, a low-wattage rheostat may be used to vary the speed of the motor due to the variation in field resistance. As field resistance increases, field current will decrease. A decrease in

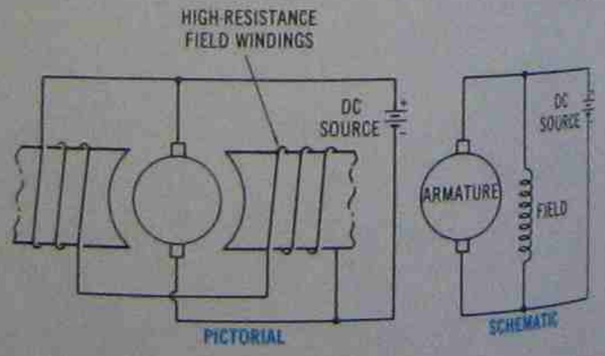


Fig. 14-6. Shunt-wound dc motor.

field current reduces the strength of the electromagnetic field. When the field flux is decreased, the armature will rotate *faster*, due to reduced magnetic-field interaction. Thus, the speed of a dc shunt motor may be easily varied by using a field rheostat.

The shunt-wound dc motor has very good speed regulation. The speed does decrease slightly when the load increases due to the increase in voltage drop across the armature. Due to its good speed regulation characteristic and its ease of speed control, the dc shunt motor is commonly used for industrial applications. Many types of variable-speed machine tools are driven by dc shunt motors.

Compound-Wound DC Motors—The compound-wound dc motor, shown in Fig. 14-7, has two sets of field windings, one in series with the armature and one in parallel. This motor combines the desirable characteristics of the series- and shunt-wound motors. It has high torque similar to a series-wound motor, along with good speed regulation similar to a shunt motor. Therefore, when good torque and good speed regulation are needed, the compound-wound dc motor can be used. A major disadvantage of a compound-wound motor is its expense.

Comparison of DC Motor Characteristics—The characteristics of dc motors should be considered when selecting motors for particular applications. Fig. 14-8 shows comparative graphs that illustrate the relative torque and speed characteristics of dc motors.

A dc motor is designed so that its shaft will rotate in either direction. It is a very simple process to reverse the direction or rotation of any dc motor. By reversing the relationship between the connections of the armature winding and field windings, reversal of rotation is

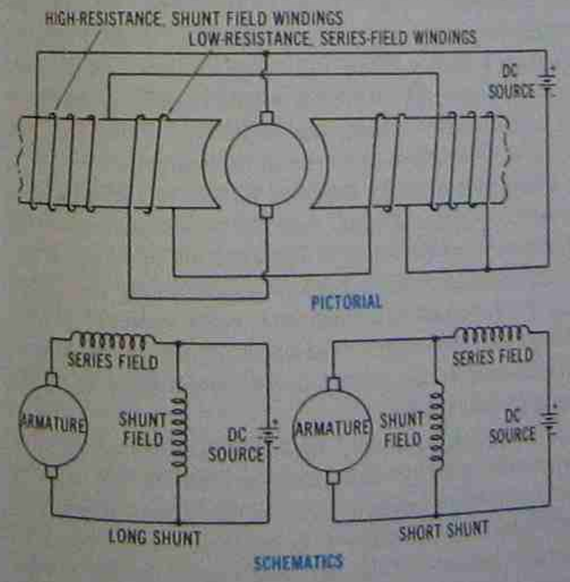
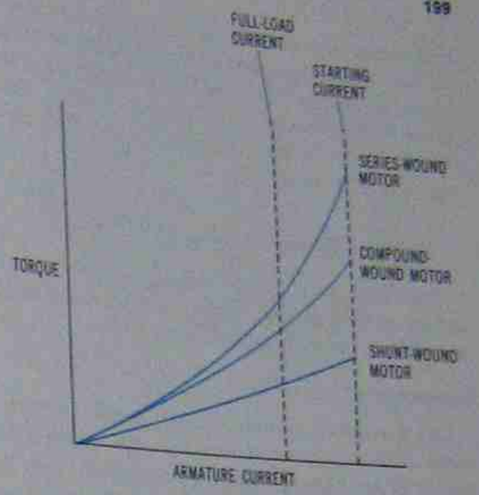
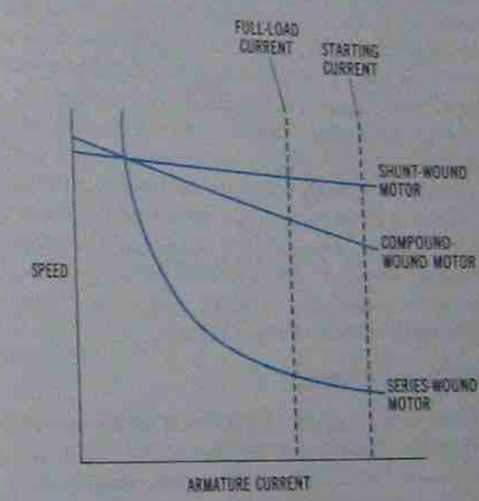


Fig. 14-7. Compound-wound dc motor.



(A) Armature current versus torque.



(B) Armature current versus speed.

Fig. 14-8. Torque and speed characteristics of dc motors.

achieved. Usually, this is done by changing the terminal connections where the power source is connected to the motor. Four terminals are ordinarily used for interconnection purposes. They may be labeled A1 and A2 for the armature connections and F1 and F2 for the

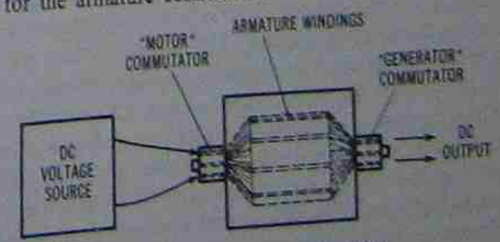


Fig. 14-9. Dynamotor construction.

field connections. If either the armature connections or the field connections are reversed, the rotation of the motor will reverse. However, if both are reversed, the motor shaft will rotate in its original direction, since the relationship between the armature and field windings would be the same.

SPECIALIZED DC MOTORS

There are several specialized types of motors which operate on direct current. Among these are dynamotors, brushless dc motors, and dc stepping motors.

Dynamotors

One specialized type of dc motor is called a dynamotor. This motor, depicted in Fig. 14-9, converts dc voltage of one value to dc voltage of another value. It is actually a motor-generator housed in one unit. The armature has two separate windings. One winding is connected to the commutator of the motor section and the other winding is connected to the commutator of a generator unit. A magnetic field, developed by either permanent magnets or electromagnetic windings, surrounds the armature assembly. Since the magnetic field remains relatively constant, the generator voltage output depends upon the ratio of the number of motor windings to the number of generator windings. For instance, if there are twice as many generator windings as motor windings, the generated dc-voltage output will be twice the value of the dc voltage that is input to the motor section of the dynamotor.

Brushless DC Motors

The use of transistors has resulted in the development of brushless dc motors which have neither brushes nor commutator assemblies. Instead, they make use of solid-state switching circuits. The major problem with most dc motors is the low reliability of the commutator/brush assembly. The brushes have a limited life and cause the commutator to wear. This wearing produces brush dust which can cause other maintenance problems.

Although some brushless dc motors use other methods, the transistor-switched motor is the most common (see Fig. 14-10). The motor itself is actually a single-phase ac permanent-capacitor induction motor with a center-tapped main winding. Transistors, that are operated by an oscillator circuit, conduct alternately through the paths of the main winding. The oscillator circuit requires a feedback winding wound into the stator slots, which generates a control voltage to determine the frequency. A capacitor (C2) is placed across the main winding to reduce voltage peaks and to keep the frequency of the circuit at a constant value.

The main disadvantage of this motor is its inability to develop a very high starting torque. As a result, it is suitable only for driving very low-torque loads. When used in a low-voltage system, this motor is not very efficient. Also, since only half of the main winding is in use at any instant, copper losses are relatively high. However, the advantages outweigh this disadvantage for certain applications. Since there are no brushes and commutator, motor life is limited mainly

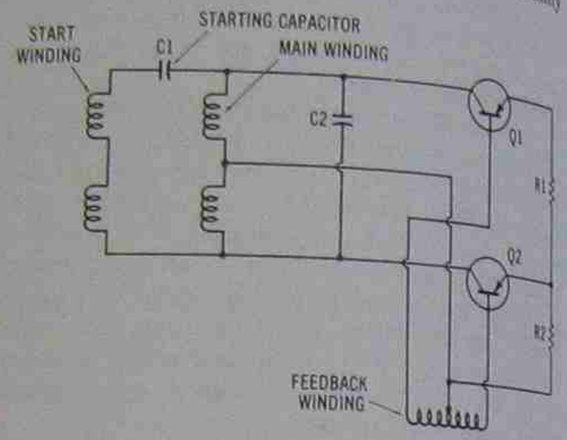


Fig. 14-10. A brushless dc motor circuit.

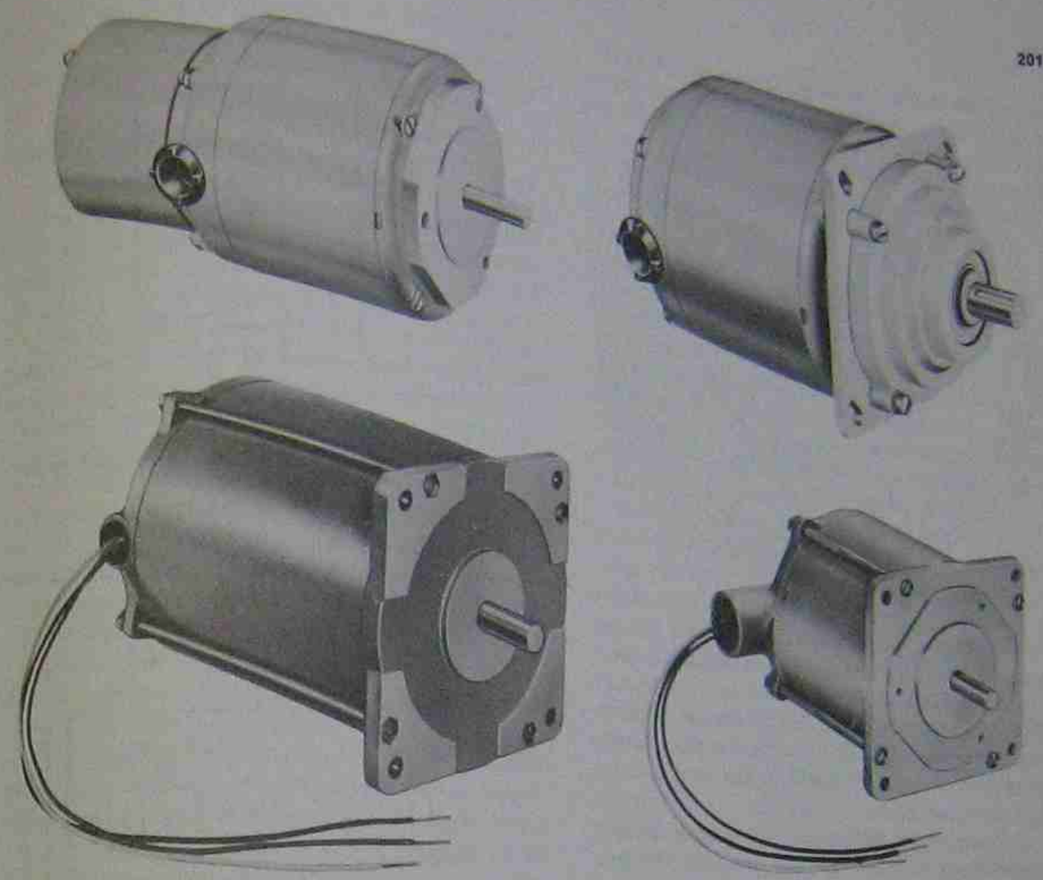
by the bearing. With proper lubrication, a brushless dc motor can be used for an indefinite period. Also, the motor frequency and, thus, the speed can be adjusted by varying the oscillator circuit.

DC Stepping Motors

Direct-current stepping motors are unique dc motors that are used to control automatic industrial processing equipment. Direct-current motors of this type are found in nearly all numerically controlled machines used by industry. They are very efficient and develop a high torque. The stepping motor is used primarily to change electrical pulses into a rotary motion that can be used to produce mechanical movements.

The shaft of a dc stepping motor rotates a specific number of mechanical degrees with each incoming pulse of electrical energy. The amount of rotary movement or angular displacement produced by each pulse can be repeated precisely with each succeeding pulse from the drive source. The resulting output of this device is used to accurately locate or position automatic process machinery.

The velocity, distance, and direction of movement of a specific machine can be controlled by dc stepping motors. The movement error of this device is generally less than 5% per step. This error factor is not cumulative regardless of the distance moved or the number of steps taken. Motors of this type are energized by a



Courtesy The Superior Electric Co.

Fig. 14-11. Dc stepping motors.

dc drive amplifier that is controlled by digital logic circuits. The drive-amplifier circuitry is a key factor in the overall performance of this motor. Some dc stepping motors are shown in Fig. 14-11. The stator construction and coil layout are shown in Fig. 14-12. The rotor of a stepping motor is of a permanent-magnet type of construction.

A very important principle that applies to the operation of a dc stepping motor is that *like* magnetic poles repel and *unlike* magnetic poles attract. If a permanent-magnet rotor were placed between two series-connected stator coils, it would produce the situation of Fig. 14-13A. With power applied to the stator, the rotor could be repelled in either direction. The direction of rotation in this case is unpredictable. Adding two more stator coils to a simple motor, as indicated in Fig. 14-13B, would make the direction of rotation predictable. With the stator polarities indicated, the rotor would align itself midway between the two pairs of stator coils. The direction of rotation can now be predicted and is determined by the polarities of the stator-coil sets. Adding more stator-coil pairs to a motor of this type improves its rotation and makes the stepping action very accurate.

Fig. 14-14 shows an electrical diagram of a dc stepping motor. The stator coils of this motor are wound by a special type of construction called *bifilar*. Two separate wires are wound into the coil slots at the same time. The two wires are smaller in size, which permits twice as many turns as could be achieved with a larger-sized wire. Construction of this type simplifies the control circuitry and dc energy-source requirements.

Operation of the stepping motor illustrated in Fig. 14-14 is achieved in a four-step switching sequence. Any of the four combinations of switches 1 or 2 will produce an appropriate rotor position location. After the four switch combinations have been achieved, the switching cycle repeats itself. Each switching combination causes the motor to move one-fourth of a step.

A rotor similar to the one shown in Fig. 14-12 normally has 50 teeth. Using a 50-tooth rotor in the circuit of Fig. 14-14 would permit four steps per tooth,

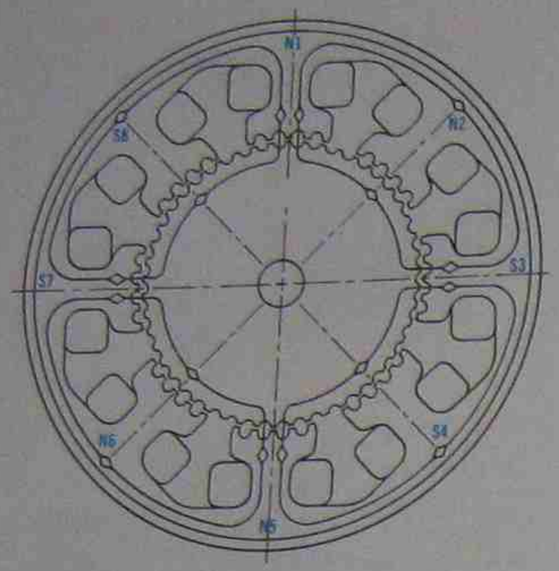


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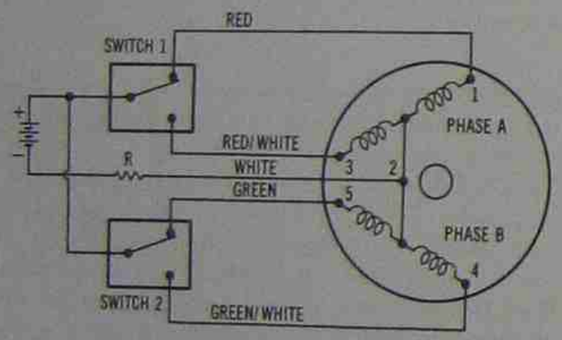
Fig. 14-12. Stator and coil layout of a dc stepping motor.

or 200 steps per revolution. The amount of displacement or step angle of this motor is, therefore, determined by the number of teeth on the rotor and the switching sequence.

A stepping motor that takes 200 steps to produce one revolution will move 360 degrees each 200 steps or 1.8 degrees per step. It is not unusual for stepping



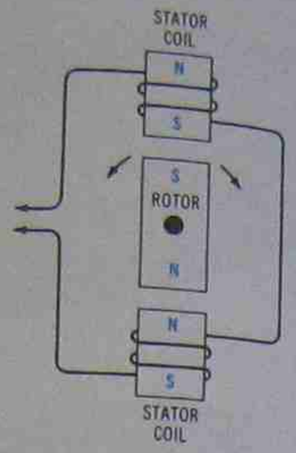
SWITCHING SEQUENCE *

STEP	SWITCH 1	SWITCH 2
1	1	5
2	1	4
3	3	4
4	3	5
1	1	5

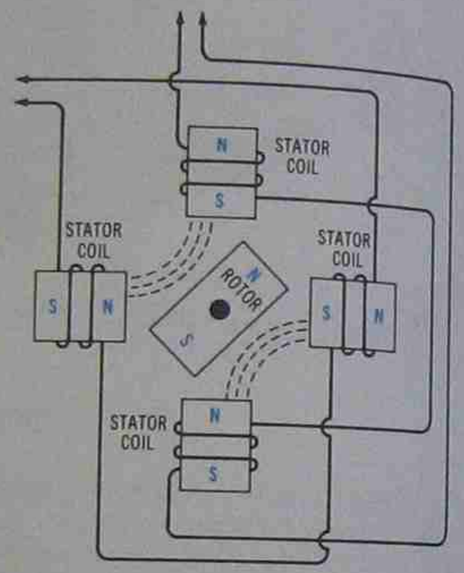
*To reverse direction, read chart up from bottom.

Courtesy The Superior Electric Co.

Fig. 14-14. Circuit diagram and switching sequence of a dc stepping motor.



(A) With one set of stator coils, direction of rotor rotation is unpredictable.



(B) With two sets of stator coils and polarities as shown, rotor will align itself as shown.

Fig. 14-13. Illustration of the magnetic principle involved in the operation of a dc stepping motor.

motors to use eight switching combinations to achieve one step. In this case, each switching combination could be used to produce 0.9 degree of displacement. Motors and switching circuits of this type permit a very precise type of controlled movement.

SINGLE-PHASE AC MOTORS

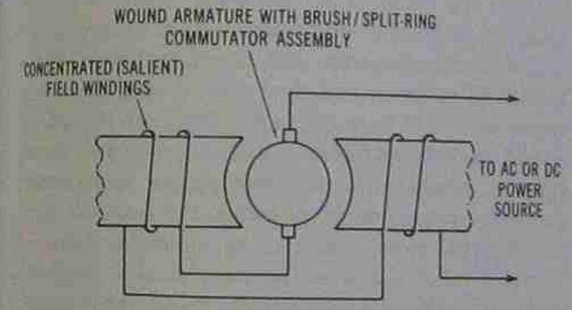
Another broad classification of mechanical power-conversion equipment includes single-phase alternating-current (ac) motors. These motors are common for industrial as well as commercial and residential usage.

They operate from a single-phase ac power source. There are three basic types of single-phase ac motors—universal motors, induction motors, and synchronous motors.

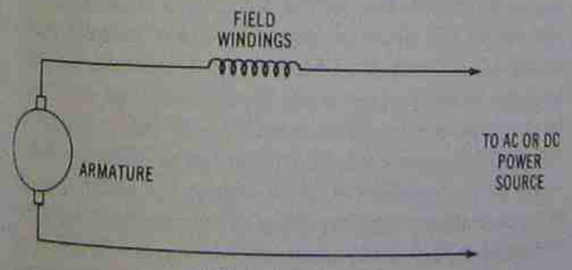
Universal Motors

Universal motors may be powered by either ac or dc power sources. The universal motor, shown in Fig. 14-15, is constructed in the same way as a series-wound dc motor. However, it is designed to operate with either ac or dc applied. The series-wound motor is the only type of dc motor which will operate with ac applied. The windings of shunt-wound motors have inductance values that are too high to allow the motor to function with ac applied. However, series-wound motors have windings that have low inductances (few turns of large diameter wire) and, therefore, offer a low impedance to the flow of alternating current. The universal motor is one type of ac motor that has concentrated or salient field windings. These field windings are similar to those of all dc motors.

The operating principle of the universal motor, with ac applied, involves the instantaneous change of both field and armature polarities. Since the field windings have low inductance, the reversals of field polarity brought about by the changing nature of the applied alternating current also create reversals of current direction through the armature conductors at the proper time intervals. The universal motor operates in the same manner as a series-wound dc motor except that the field polarity and the direction of armature current change at a rate of 120 times per second when connected to a 60-Hz ac source. The speed and torque characteristics of universal motors are similar to dc series-wound motors. Universal motors are used mainly for portable tools and small motor-driven equipment, such as mixers and blenders.



(A) Schematic diagram.



(B) Pictorial diagram.

Fig. 14-15. The universal motor.

Induction Motors

Another popular type of single-phase ac motor operates on the induction principle. This principle is illustrated in Fig. 14-16. The coil symbols along the stator represent the field coils of an induction motor. These coils are energized by an alternating-current source; therefore, their instantaneous polarity changes 120 times per second when 60-Hz ac is applied.

Induction motors have a solid rotor which is referred to as a *squirrel-cage* rotor. This type of rotor, which is illustrated in Fig. 14-16B, has large-diameter copper conductors that are soldered at each end to a circular connecting plate. This plate actually short circuits the individual conductors of the rotor. When current flows in the stator windings, a current is induced in the rotor. This current is developed due to "transformer action" between the stator and rotor. The stator, which has ac voltage applied, acts as a transformer primary. The rotor is similar to a transformer secondary since current is induced into it.

Since the stator polarity changes in step with the applied ac, it develops a rotating magnetic field. The rotor becomes instantaneously polarized due to the induced current flow through the short-circuited copper conductors. The rotor will, therefore, tend to rotate in step with the revolving magnetic field of the stator. If some method of initially starting rotation is used, the rotor will continue to rotate. However, due to inertia, a rotor must be put into motion initially by some auxiliary method.

It should be pointed out that the speed of an ac induction motor is based on the speed of the rotating magnetic field and the number of stator poles that the motor has. The speed of the rotor will never be as high as the speed of the rotating stator field. If the two speeds were equal, there would be no relative motion between the rotor and stator and, therefore, no induced rotor current and torque developed. The rotor speed (operating speed) of an induction motor is always somewhat less than the rotating stator field developed by the applied ac voltage.

The speed of the rotating stator field may be expressed as:

$$S = \frac{f \times 120}{n}$$

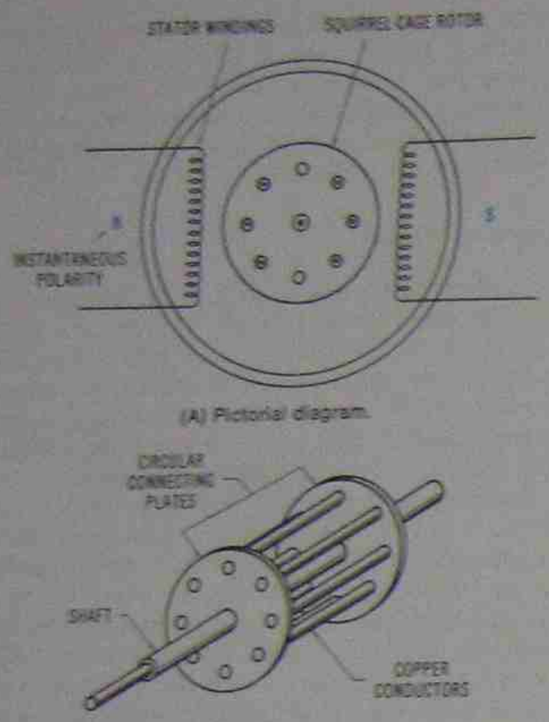


Fig. 14-16. Illustration of the induction principle.

where,

S is the speed of the rotating stator field in rpm,
f is the frequency of the applied ac voltage in hertz,
n is the number of poles in the stator windings,
120 is a conversion constant.

A two-pole motor operating from a 60-Hz source would have a stator speed of 3600 revolutions per minute. The stator speed is also referred to as the *synchronous* speed of a motor.

The difference between the revolving stator speed of an induction motor and the rotor speed is called *slip*. The rotor speed must lag behind the revolving stator speed in order to develop torque. The more the rotor speed lags behind, the more torque is developed. Slip is expressed mathematically as:

$$\% \text{ slip} = \frac{S_s - S_r}{S_s} \times 100$$

where,

S_s is the synchronous (stator) speed in rpm,
S_r is the rotor speed in rpm.

As the rotor speed becomes closer to the stator speed, the percentage of slip becomes smaller.

Another factor, referred to as *rotor frequency*, affects the operational characteristics of an induction motor under load. As the load on the shaft of the motor increases, the rotor speed tends to decrease. The stator

speed, however, is unaffected. When a two-pole induction motor connected to a 60-Hz source operates at 10% slip, the slip would equal 360 rpm (3600 rpm × 10%). Functionally, this means that a revolving stator field sweeps across a rotor conductor 360 times per minute. Current is induced into a rotor conductor each time the stator field revolves past the conductor. As slip is increased, more current is induced into the rotor, causing more torque to be developed. The rotor frequency depends on the amount of slip and can be expressed as:

$$f_r = f_s \times \text{slip}$$

where,

f_r is the frequency of the rotor current,
f_s is the frequency of the stator current,
slip is expressed as a decimal.

Rotor frequency affects the operational characteristics of induction motors.

Single-phase ac induction motors are classified according to the method used for starting. Some common types of single-phase ac induction motors include *split-phase* motors, *capacitor* motors, *shaded-pole* motors, and *repulsion* motors.

Split-Phase Induction Motors—The split-phase ac induction motor, shown in Fig. 14-17, has two sets of stator windings. One set, called the *run windings*, is connected directly across the ac line. The other set, called the *start windings*, is also connected across the ac line. However, the start winding is connected in series with a centrifugal switch that is mounted on the shaft of the motor. The centrifugal switch is in the closed position when the motor is not rotating.

Before discussing the functional principle of the split-phase ac motor, we should understand how rotation is developed by an ac motor. Refer to Fig. 14-18. In Fig. 14-18A, we have a two-pole stator with single-phase ac applied. For purposes of our discussion, a permanent magnet is placed within the stator to represent the squirrel-cage rotor of an induction motor. At time t_0 of the ac sine wave, no stator field is developed. Time interval t_1 will cause a stator field to be produced. Assume a north polarity on the right pole of the stator and a south polarity on the left pole. These polarities will cause the rotor to align itself horizontally based on the laws of magnetic attraction. At time t_2, the poles become demagnetized and, then, begin to magnetize in the opposite direction. At time interval t_3, the stator poles are magnetized in the opposite direction. The rotor will now align itself horizontally as before but in the opposite direction. This effect would continue at a rate of 120 polarity changes per second if 60-Hz ac is applied to the stator. The rotor would not start unless it was positioned initially to be drawn toward a

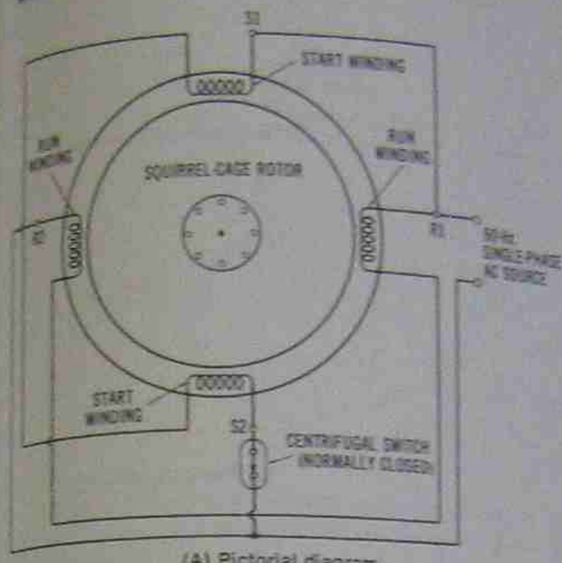


Fig. 14-17. The split-phase induction motor.

pole piece. Therefore, some starting method must be used for single-phase ac motors, since they are not self-starting.

Assume that we have a two-phase situation as shown in Fig. 14-18B. We now have two sets of stator windings with one phase connected to each set. Two-phase voltage is, of course, not produced by power companies in the United States; however, this example will show the operational principle of a split-phase motor. As shown in the two-phase voltage-curve diagram, when one phase is at minimum value, the other is maximum.

At time interval t_1, phase 1 is maximum while phase 2 is minimum. Assume that the right stator pole becomes a north polarity and the left pole becomes a south polarity. The rotor will align itself horizontally since no polarity is developed in the vertical poles at this time. Now, as we progress to time t_2, phase 1 is a minimum and phase 2 is maximum. Assume that the upper stator pole becomes a south polarity and the bottom stator pole becomes a north polarity. The rotor will now align itself vertically, by moving 90°. At time t_3, phase 1 becomes maximum in the opposite direction and phase 2 is minimum. This time interval results in a north pole on the left and a south pole on the right.

Thus, the rotor moves 90° further in a clockwise direction. This effect will continue as two-phase voltage is applied to the stator poles. We can see from the two-phase situation that a direction of rotation is established by the relationship of the phase 1 and the phase 2 curves and that an ac motor with two-phase voltage applied would be self-starting.

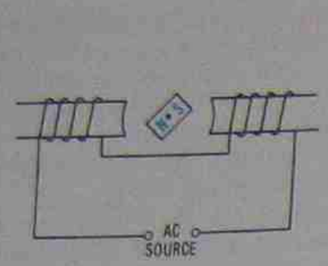
The same is true for a three-phase situation, such as is illustrated in Fig. 14-18C. Rotation of the rotor would result because of the 120° phase separation of the three-phase voltage applied to the stator poles. Three-phase induction motors are, therefore, self-starting with no auxiliary starting method required.

Going back to the split-phase motor of Fig. 14-17, we can see that the purpose of the two sets of windings is to establish a simulated two-phase condition to start the motor. The single-phase voltage applied to this motor is said to be "split" into a two-phase current. A rotating or revolving magnetic field is created by phase splitting. The start winding of the split-phase motor is made of a relatively few turns of small diameter wire, giving it a high resistance and a low inductance. The run winding is wound with many turns of large diameter wire, causing it to have a lower resistance and a higher inductance. We know that inductance in an ac circuit causes the current to lag the applied ac voltage. The more inductance present, the greater is the lag in current.

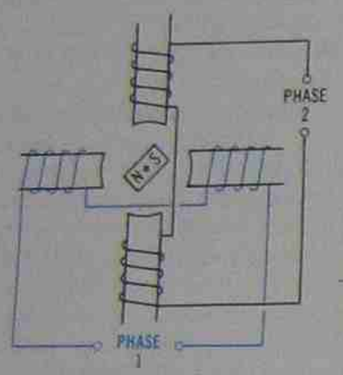
When single-phase ac is applied to the stator of a split-phase induction motor, the situation illustrated in Fig. 14-19 would result. Notice that the current in the start winding lags the applied voltage due to its inductance. However, the current in the run windings lags by a greater amount due to its higher inductance. The phase separation of the currents in the start and run windings creates a two-phase situation. The phase displacement, however, is usually around 30° or less, which gives the motor a low starting torque since this phase separation does not nearly approach the 90° separation of two-phase voltage. When the split-phase ac induction motor reaches about 80% of its normal operating speed, the centrifugal switch will open the start winding circuit since it is no longer needed. The removal of the start winding minimizes energy losses in the machine and prevents the winding from overheating. When the motor is turned off and its speed reduced, the centrifugal switch closes to connect the start winding back into the circuit.

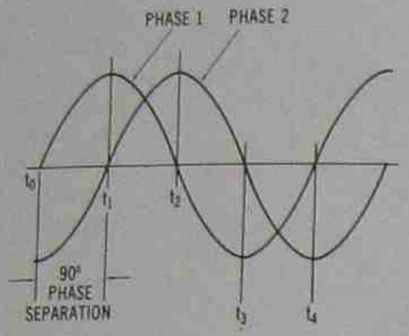
Split-phase motors are fairly inexpensive compared to other types of single-phase motors. They are used where low torque is required to drive mechanical loads such as small machinery.

Capacitor Motors—Capacitor motors, such as the one shown in Fig. 14-20, are an improvement over the

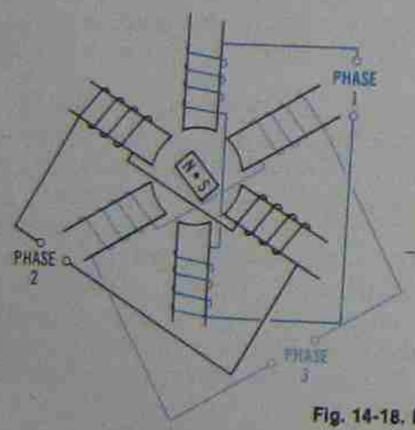


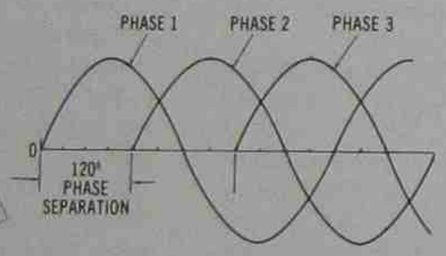
(A) Single-phase situation.





(B) Two-phase situation.





(C) Three-phase situation.

Fig. 14-18. Illustration of how ac motors develop rotation.

split-phase ac motor. Notice, in this cutaway illustration, some of the internal features of induction motors. All induction motors have squirrel-cage rotors that look similar to the one shown in the illustration. You can, also, clearly see the centrifugal switch assembly and the start and run windings. Also, notice the location of the starting capacitor. The wiring diagram of a capacitor-start single-phase induction motor is shown in Fig. 14-21A. Notice that, except for a capacitor placed in series with the start winding, this diagram is the same as for the split-phase motor. The purpose of the capacitor is to cause the current in the start winding to lead (rather than lag) the applied voltage. This situation is illustrated by the voltage/current curves shown in Fig. 14-22. The current in the start winding now leads the applied voltage due to the high value of capacitance in the circuit. Since the run winding is highly inductive, the current through it lags the applied voltage. Notice that the amount of phase separation now approaches 90°, or an actual two-phase situation. The starting torque produced by a capacitor-start induction motor is much greater than that of a split-phase motor. Thus, this type of motor can be used for applications requiring greater initial torque. However, they are somewhat more expensive than split-phase ac motors. Most capacitor motors, as well as split-phase motors, are used in fractional-horsepower sizes (less than one hp).

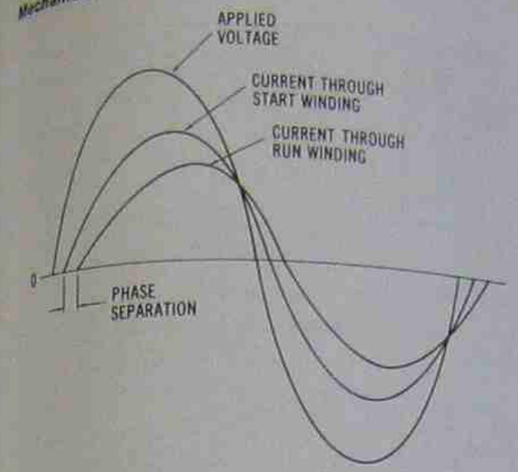
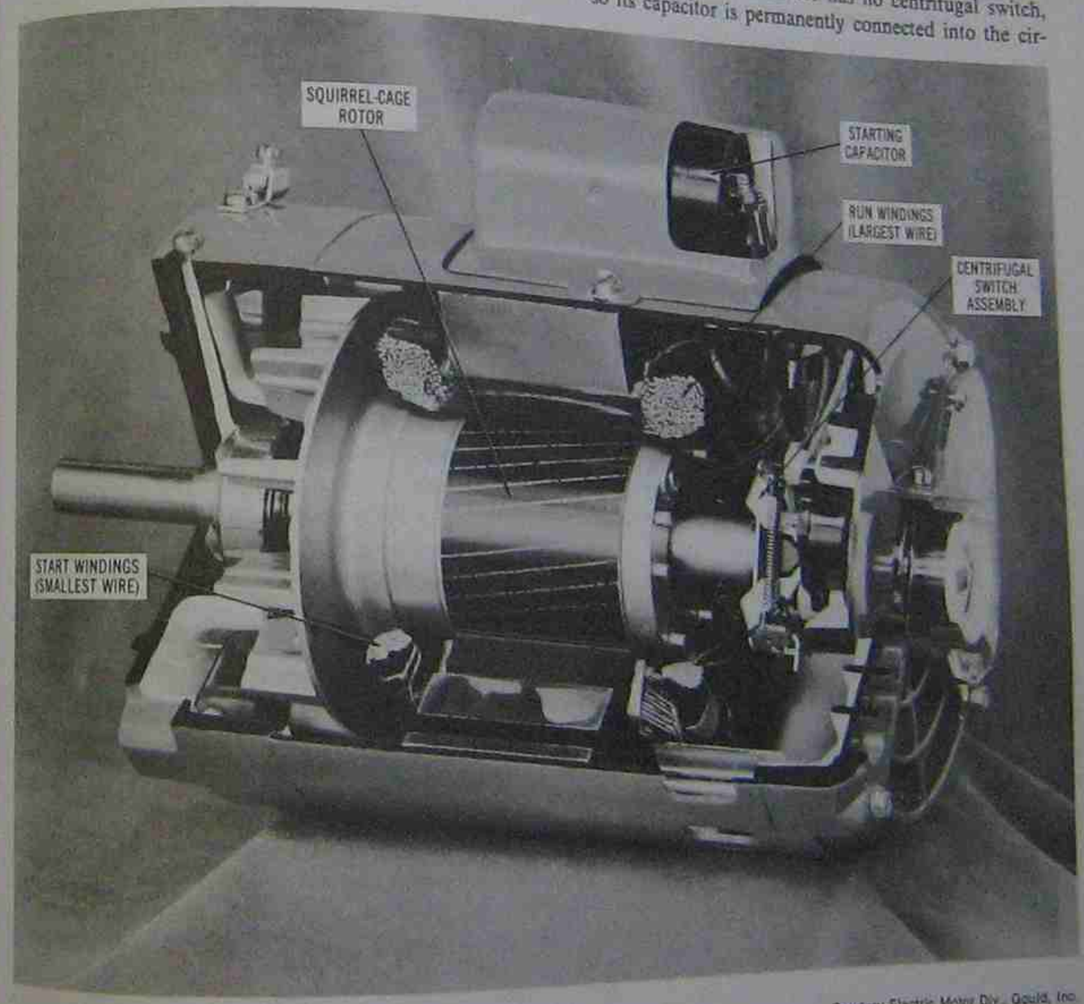


Fig. 14-19. Voltage/current relationships in a split-phase induction motor.

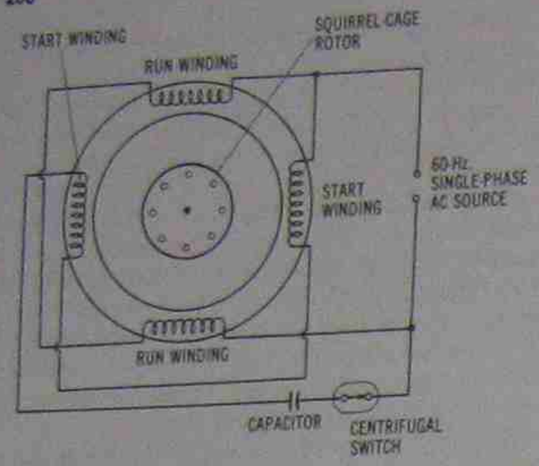
Another type of capacitor motor is called a *capacitor-start, capacitor-run,* or *two-value capacitor* motor. Its circuit is shown in Fig. 14-23A. This motor employs two capacitors. One, of low value, is in series with the start winding and remains in the circuit during operation. The other, of higher value, is in series with the start winding and a centrifugal switch. The larger capacitor is used only to increase starting torque and is removed from the circuit during normal operation by the centrifugal switch. The smaller capacitor and the entire start winding are part of the operational circuit of the motor. The smaller capacitor helps to produce a more constant-running torque, as well as quieter operation and an improved power factor.

Still another type of capacitor motor is one that is called a *permanent capacitor* motor. Its circuit is shown in Fig. 14-23B. This motor has no centrifugal switch, so its capacitor is permanently connected into the cir-

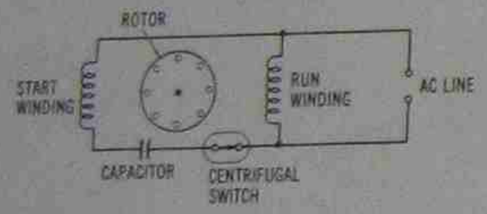


Courtesy Electric Motor Div., Gould, Inc.

Fig. 14-20. Cutaway view of a single-phase capacitor-start induction motor.



(A) Pictorial diagram.



(B) Schematic diagram.

Fig. 14-21. The capacitor-start single-phase induction motor.

cuit. These motors are only used for very low-torque requirements and are made in small fractional-horsepower–size units.

Both split-phase motors and capacitor motors may have their direction of rotation reversed easily. Simply change the relationship of the start winding and the run winding. By reversing either the start winding connections or the run winding connections (but not both), the rotational direction will be reversed.

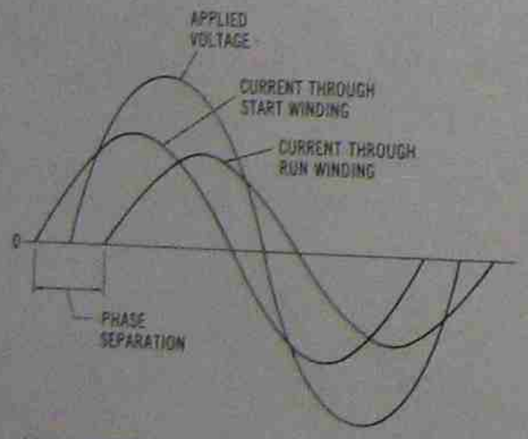
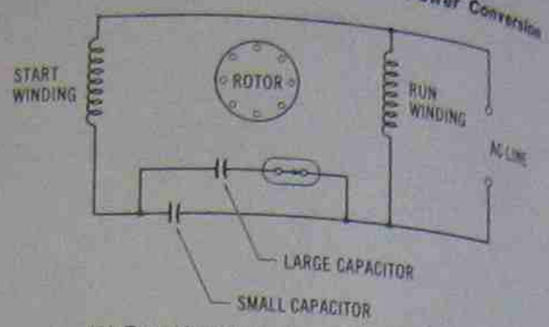
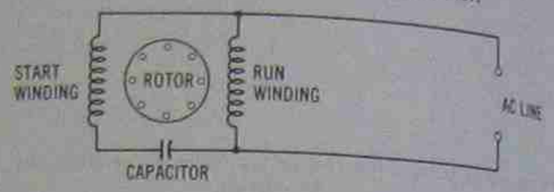


Fig. 14-22. Voltage/current relationships in a capacitor-start single-phase induction motor.



(A) Capacitor-start, capacitor-run motor.



(B) Permanent capacitor motor.

Fig. 14-23. Other types of capacitor motors.

Shaded-Pole Induction Motors—Another method of producing torque by a simulated two-phase method is called *pole shading*. A shaded-pole motor is shown in Fig. 14-24. These motors are used for very low-torque applications such as fans and blower units. They are low-cost, rugged, and reliable motors that ordinarily come in low horsepower ratings, from 1/300 to 1/8 hp, with some exceptions.

The operational principle of a shaded-pole motor is shown in Fig. 14-25. The single-phase alternation shown is for discussion purposes only. The dotted lines represent induced voltage into the shaded section of the field poles. Note the shading coils in the upper right and lower left of the two poles. The shaded pole is encircled by a heavy copper conductor and is actually a part of the main field pole. This closed-loop conductor will cause current to be induced into it when ac is applied to the field.

When an ac voltage is applied to the stator windings, the magnetic flux in the main poles induces a voltage into the shaded sections of the poles. Since the shaded section acts like a transformer secondary, its voltage is out of phase with the main field voltage as shown in the waveform diagram of Fig. 14-25A. Note the four time intervals that are shown in sequence in Fig. 14-25. The voltage induced in the shaded pole from the main pole field causes movement of the rotor to continue. Study Fig. 14-25 carefully to understand the basic operating principle of the shaded-pole ac induction motor more fully.

The shaded-pole motor is inexpensive since it uses a squirrel-cage rotor and has no auxiliary starting winding or centrifugal mechanism. Application is limited

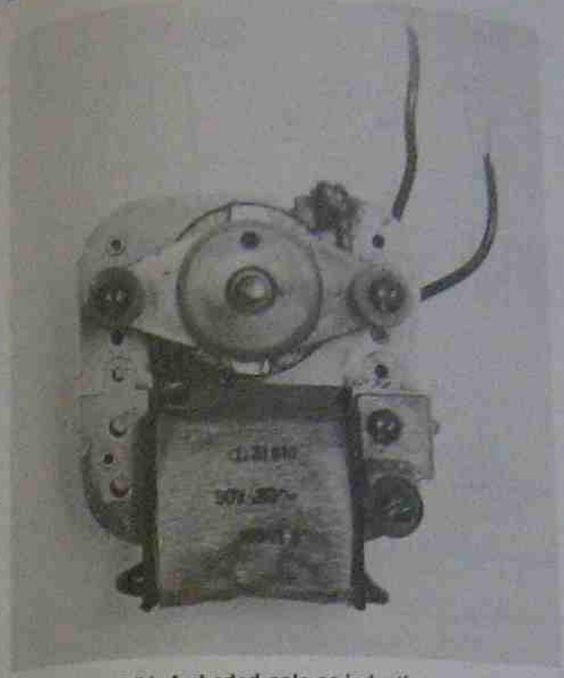


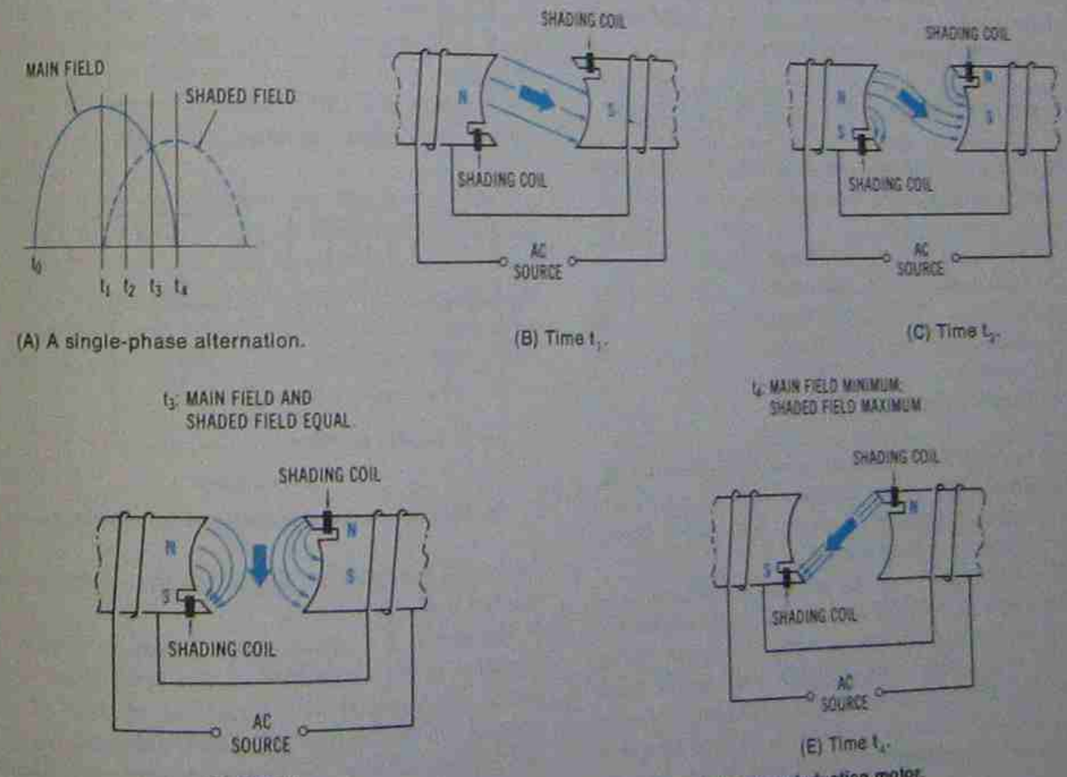
Fig. 14-24. A shaded-pole ac induction motor.

mainly to small fans and blowers and other low-torque applications.

Repulsion Motors—Another type of ac induction motor is the *repulsion-start* induction motor. This motor was used for many applications, but is now being replaced by other types of single-phase motors. The principle of operation of the repulsion motor is an interesting contrast to other induction motors.

Fig. 14-26 shows the operational principle of the repulsion motor. This motor has a *wound rotor* which functions similar to a squirrel-cage rotor. It also has a commutator/brush assembly. The brushes are shorted together to produce an effect similar to the shorted conductors of a squirrel-cage rotor. The position of the brush axis determines the amount of torque developed and the direction of rotation of the repulsion motor.

In position 1, Fig. 14-26A, the brush axis is horizontally aligned with the stator poles. Equal and opposite currents are now induced into both halves of the rotor. Thus, no torque is developed with the brushes in this position. In position 2, (Fig. 14-26B), the brushes are placed at a 90° angle to the stator field poles. The voltages induced into the rotor again coun-



(A) A single-phase alternation.
(B) Time t_1.
(C) Time t_2.
(D) Time t_3.
(E) Time t_4.

Fig. 14-25. Illustration of the operational principle of the shaded-pole ac induction motor.

teract one another and no torque is developed. In position 3 (Fig. 14-26C), the brush axis is shifted about 60° from the stator poles. The current flow in the armature now causes a magnetic field to exist around the rotor. The rotor field will now follow the revolving stator field in a clockwise direction. As might be expected, if we shift the brush axis in the opposite direction as shown in position 4 (Fig. 14-26D), rotation reversal will result. Thus, magnetic repulsion between the stator field and the induced rotor field causes the rotor to turn in the direction of the brush shift.

Repulsion-start induction motors and some similar types of modified repulsion motors have very high starting torque. Their speed may be varied by varying the position of the brush axis. However, the mechanical problems inherent with this type of motor have caused it to become obsolete.

Single-Phase Synchronous Motors

It is often desirable, in timing or clock applications, to use a constant-speed drive motor. Such a motor, which operates from a single-phase ac line, is called a *synchronous* motor. The single-phase synchronous motor has stator windings which are connected across the ac line. Its rotor is made of a permanent magnetic material. Once the rotor is started, it will rotate in synchronism with the revolving stator field, since it does not rely upon the induction principle. The calculation of the speeds of synchronous motors is based on the speed formula. This formula states that

$$\text{revolutions per minute} = \frac{\text{frequency} \times 60}{\text{number of pairs of poles}}$$

Therefore, for 60-Hz operation, the following synchronous speeds would be obtained:

1. Two-pole	3600 rpm.
2. Four-pole	1800 rpm.
3. Six-pole	1200 rpm.
4. Eight-pole	900 rpm.
5. Ten-pole	720 rpm.
6. Twelve-pole	600 rpm.

Small synchronous motors are used in single-phase applications for low torque applications. Such applications include clocks, phonograph drives, and timing devices which require constant speeds.

The construction of an ac synchronous motor is quite simple. It contains no brushes, commutators, slip rings, or centrifugal-force switches. As shown in Fig. 14-27, it is simply made up of a rotor and a stator assembly. There is no direct physical contact between the rotor and stator. A carefully maintained air gap is always present between the rotor and stator. As a result of this construction, the motor has a long operating life and is highly reliable.

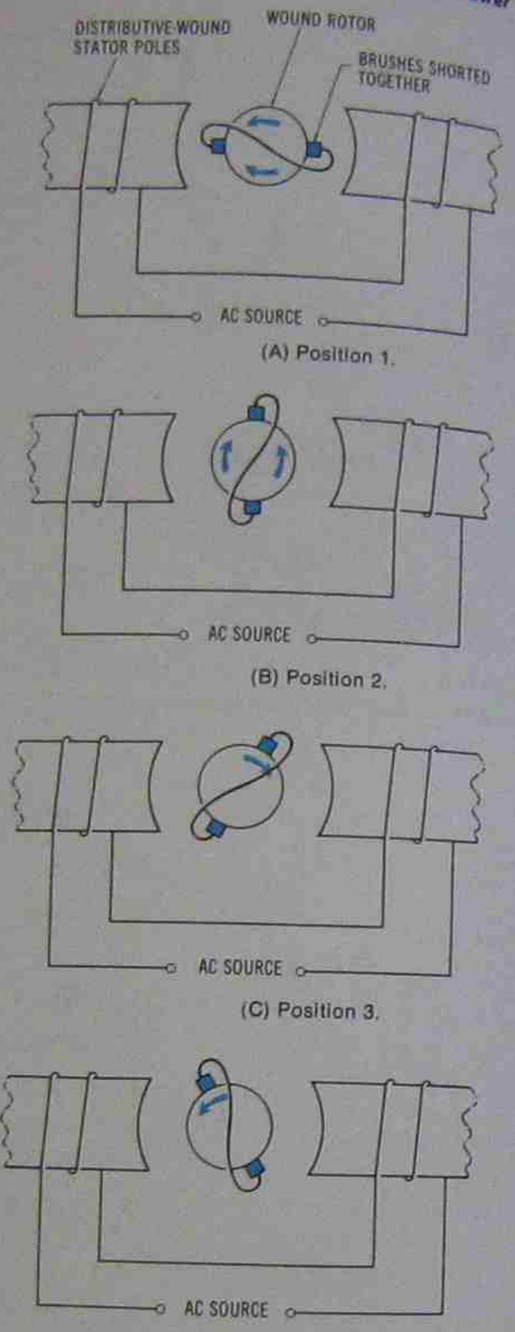


Fig. 14-26. Operational principle of the repulsion motor.

The speed of a synchronous motor is directly proportional to the frequency of the applied ac and inversely proportional to the number of pairs of stator poles. Since the number of stator poles cannot be effectively altered after the motor has been manufactured, frequency is the most significant speed factor. Speeds

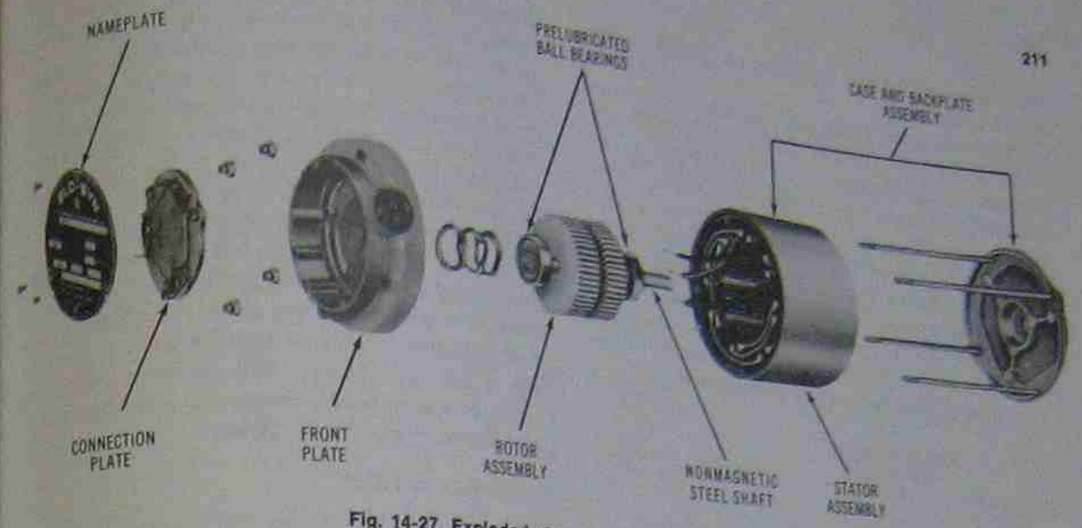


Fig. 14-27. Exploded view of an ac synchronous motor.

Courtesy The Superior Electric Co.

of 28, 72, and 200 rpm are typical, with 72 rpm being a common industrial numerical control standard.

The stator layout of a two-phase synchronous motor with four poles per phase is the same as that of the dc stepping motor shown in Fig. 14-12. Refer now to Fig. 14-12. In the diagram shown, poles N1–S3 and N5–S7 represent one phase while poles N2–S4 and N6–S8 represent the second phase. There are places for 48 teeth around the inside of the stator. One tooth per pole, however, has been eliminated to provide a space for the windings. Five teeth per pole, or a total of 40 teeth, are formed on the stator. The four coils of each phase are connected in series to achieve the correct polarity.

The rotor of the synchronous motor illustrated in Fig. 14-27 is an axially magnetized permanent magnet. There are 50 teeth cast into its form. The front section of the rotor has one polarity while the back section has the opposite polarity. The physical difference in the number of stator teeth (40) and rotor teeth (50) means that only two teeth of each part can be properly aligned simultaneously. With one section of the rotor being a north pole and the other section being a south pole, the rotor has the ability to stop very quickly. It can also produce complete direction reversals without hesitation because of this gear-like construction.

A circuit diagram of a single-phase synchronous motor is shown in Fig. 14-28. The resistor and capacitor of this circuit are used to produce a 90° phase shift in one winding. As a result, the two windings are always out of phase regardless of whether the switch is in the clockwise (cw) or counterclockwise (ccw) position. When power is applied, the four coils of one phase produce an electromagnetic field. The rotor is attracted and aligns itself to these stator coils. Then, 90° later, the four coils of the second phase produce a corresponding field. The stator is again attracted to this position. As a result of this action, the rotor "sees" a moving force across first one phase and then the other. This force gives the rotor the needed torque

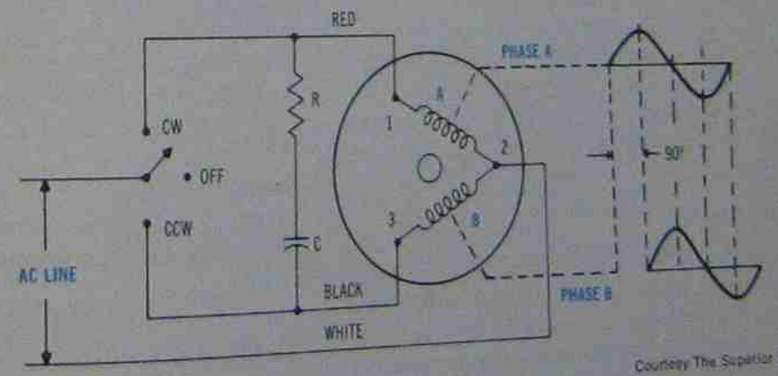


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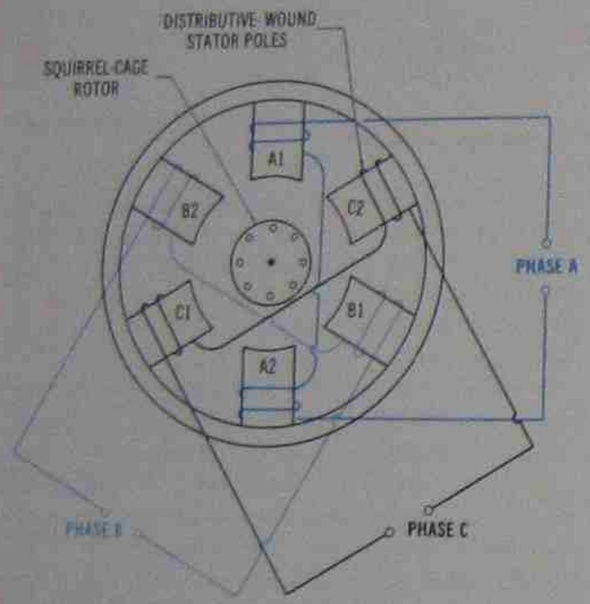
Fig. 14-28. Circuit diagram of a single-phase synchronous motor.

that causes it to start and continue rotation when power is applied.

The synchronous motor just described has the capability of starting in one and one-half cycles of the applied line-voltage frequency. In addition to this, it can be stopped in five mechanical degrees of rotation. These two characteristics are primarily attributed to the geared rotor and stator construction. Synchronous motors of this type have one other important characteristic—they draw the same amount of line current when stalled that they do when operating. This characteristic is very important in automatic machine-tool applications where overloads occur frequently.



NOTE: Stator windings may be connected in either a wye or a delta configuration.

Fig. 14-29. Pictorial diagram of the construction of a three-phase induction motor.

THREE-PHASE AC MOTORS

Three-phase ac motors are often called the "workhorses of industry." Most motors used in industry and several in commercial buildings are operated from three-phase power sources. There are three basic types of three-phase motors: (1) induction motors, (2) synchronous motors, and (3) wound-rotor induction motors (wrim).

Induction Motors

A pictorial diagram of the construction of a three-phase induction motor is given in Fig. 14-29. Note that the construction of this motor is very simple. It has only a distributive-wound stator which is connected in either a wye or a delta configuration, and a squirrel-cage rotor. Since three-phase voltage is applied to the stator, phase separation is already established (Fig. 14-30). No external starting mechanisms are needed. Three-phase induction motors come in a variety of integral horsepower sizes and have good starting and running torque characteristics. A cutaway view of a three-phase induction motor is shown in Fig. 14-31. Notice the parts of the motor which are labeled.

The direction of rotation of a three-phase motor of any type can be changed very easily. If any two power lines coming into the stator windings are reversed, the direction of rotation of the shaft will change. Three-phase induction motors are used for many applications, such as mechanical-energy sources for machine tools, pumps, elevators, hoists, conveyors, and other systems which use large amounts of power.

Synchronous Motors

Three-phase synchronous motors are unique and very specialized motors. They are considered a constant-speed motor and they can be used to correct the power factor of three-phase systems. Fig. 14-32 shows some large three-phase synchronous motors. They are usually very large in size and horsepower rating.

Figure 14-33 shows a pictorial diagram of the construction of a three-phase synchronous motor. Physically, this motor is constructed like a three-phase alternator (see Chapter 4). Direct current is applied to the rotor to produce a rotating electromagnetic field; the stator windings are connected in either a wye or delta configuration. The only difference is that three-phase ac power is applied to the synchronous motor, while three-phase power is extracted from the alternator. Thus, the motor acts as an electrical load, while the alternator functions as a source of three-phase power. This relationship should be kept in mind during the following discussion.

The three-phase synchronous motor differs from the three-phase induction motor in that the rotor is wound and is connected through a slip ring/brush assembly to a dc power source. Three-phase synchronous motors, in their pure form, have no starting torque. Some external means must be used to initially start the motor. Synchronous motors are constructed so that they will rotate at the same speed as the revolving stator field. We can say that at synchronous speed, rotor speed equals stator speed and the motor has zero slip. Thus, we can determine the speed of a synchronous motor by using the following formula:

$$S = \frac{f \times 120}{n/3}$$

where,

S is the speed of a synchronous motor in r/min,
f is the frequency of the applied ac voltage in hertz,

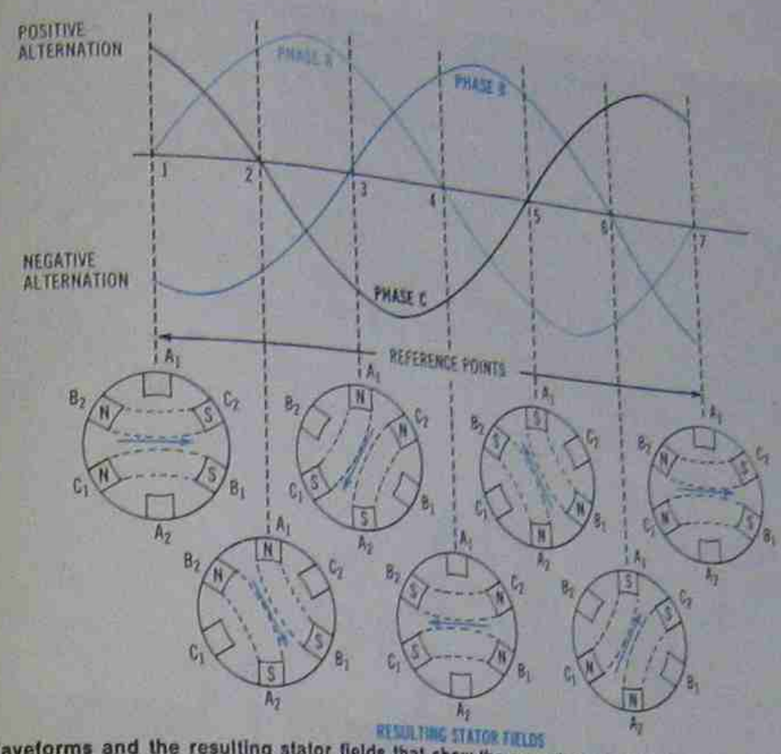
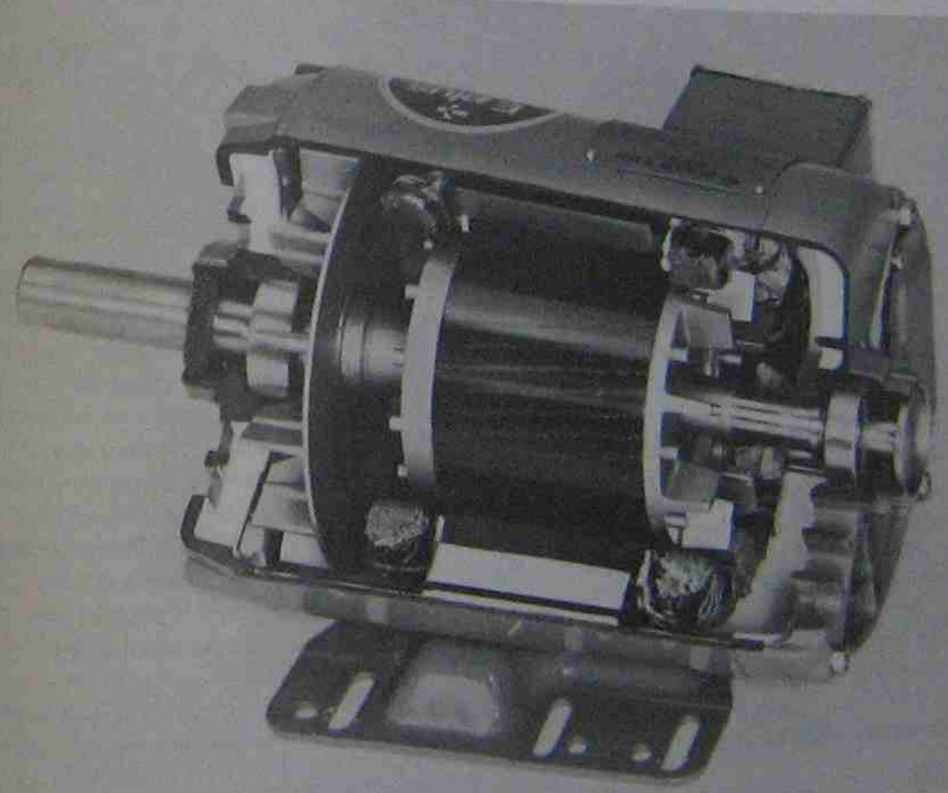
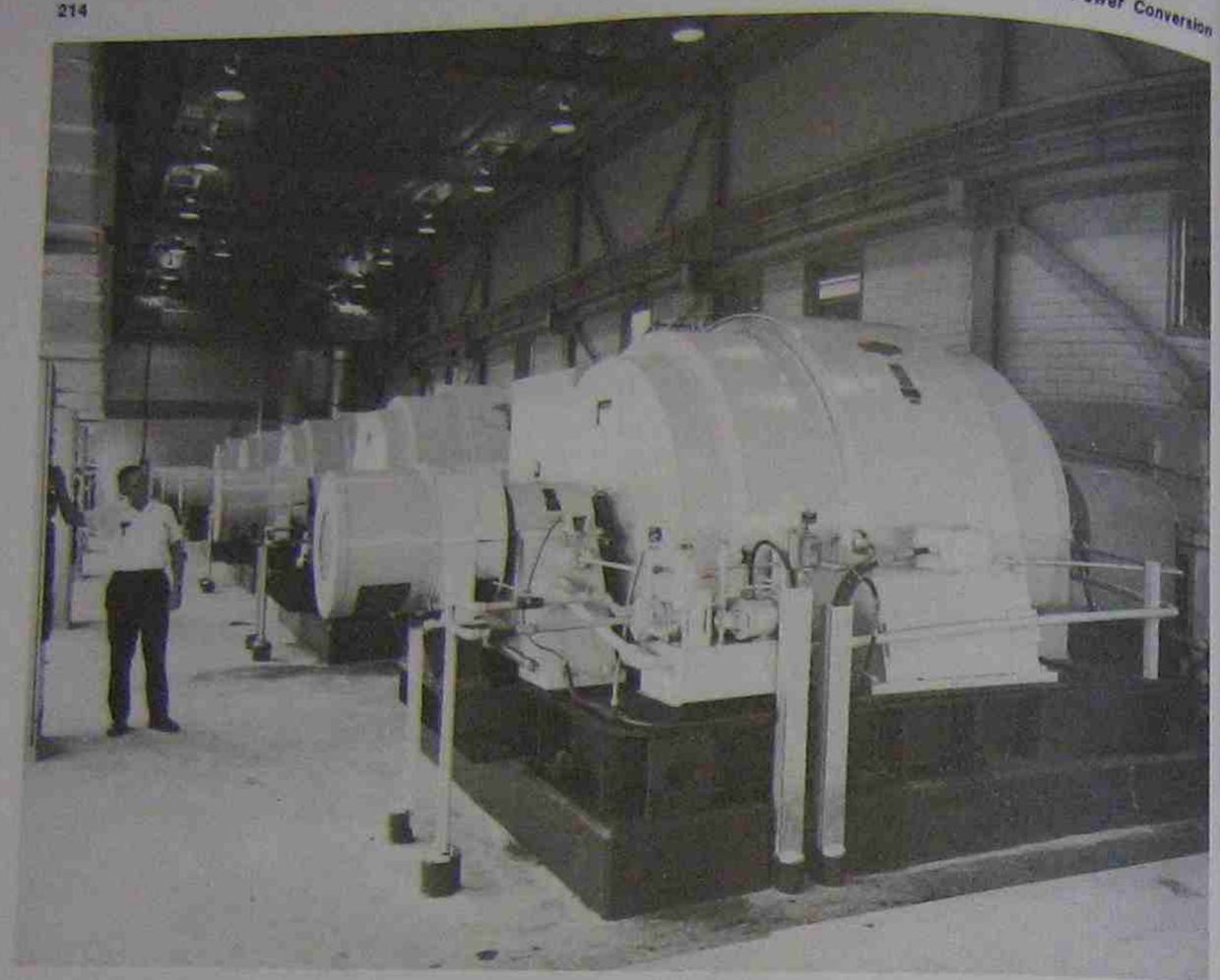


Fig. 14-30. Waveforms and the resulting stator fields that show the operating principle of a three-phase induction motor.



Courtesy Electric Motor Div., Gould, Inc.

Fig. 14-31. Cutaway view of a three-phase ac induction motor.



Courtesy Electric Machinery Manufacturing Co

Fig. 14-32. Large three-phase synchronous motors.

n/3 is the number of stator poles per phase,
120 is a conversion constant.

Note that this is the same as the formula used to determine the stator speed of a single-phase motor except that the number of poles must be divided by three (the number of phases). A three-phase motor with twelve actual poles would have four poles per phase. Therefore, its stator speed would be 1800 rpm. Synchronous motors have operating speeds that are based on the number of stator poles they have.

Three-phase synchronous motors usually are employed in very large horsepower ratings. One method of starting a large synchronous motor is to use a smaller auxiliary dc machine connected to the shaft of the synchronous motor, as illustrated in Fig. 14-34A. The method of starting would be as follows:

Step 1. Dc power is applied to the auxiliary motor, causing it to increase in speed. Three-phase ac power is applied to the stator.

Step 2. When the speed of rotation reaches a value near the synchronous speed of the motor, the dc power circuit is opened and, at the same time, the terminals of the auxiliary machine are connected across the slip ring/brush assembly of the rotor.

Step 3. The auxiliary machine now converts to generator operation and supplies exciter current to the rotor of the synchronous motor, using the motor as its prime mover.

Step 4. Once the rotor is magnetized, it will "lock" in step or synchronize with the revolving stator field.

Step 5. The speed of rotation will remain constant under changes in load condition.

Another starting method is shown in Fig. 14-34B. This method utilizes *damper* windings, which are similar to the conductors of a squirrel-cage rotor. These

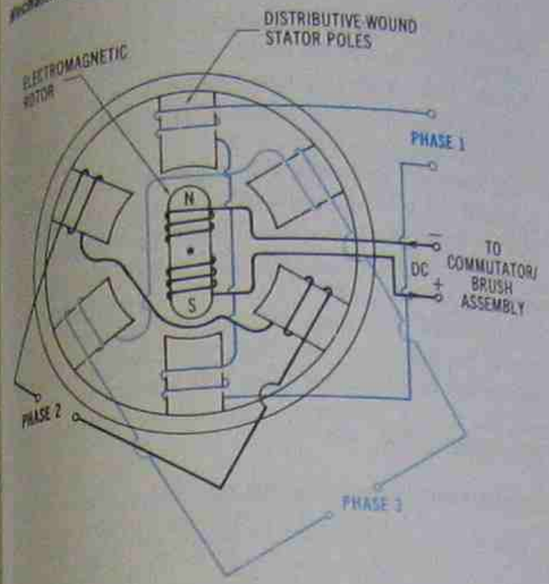


Fig. 14-33. Pictorial diagram of three-phase synchronous motor construction.

windings are placed within the laminated iron of the rotor assembly. No auxiliary machine is required when damper windings are used. The starting method used is as follows:

Step 1. Three-phase ac power is applied to the stator windings.

Step 2. The motor will operate as an induction motor due to the "transformer action" of the damper windings.

Step 3. The motor speed will build up so that the rotor speed is somewhat less than the speed of the revolving stator field.

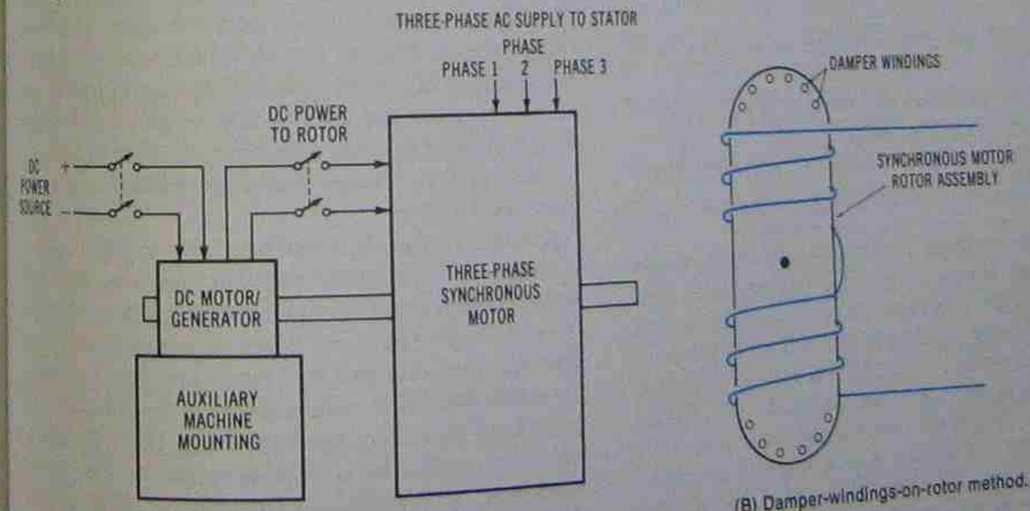
Step 4. Dc power from a rotating dc machine or, more commonly, a rectification system is applied to the slip ring/brush assembly of the rotor.

Step 5. The rotor becomes magnetized and builds up speed until rotor speed is equal to stator speed.

Step 6. The speed of rotation remains constant regardless of the load placed on the shaft of the motor.

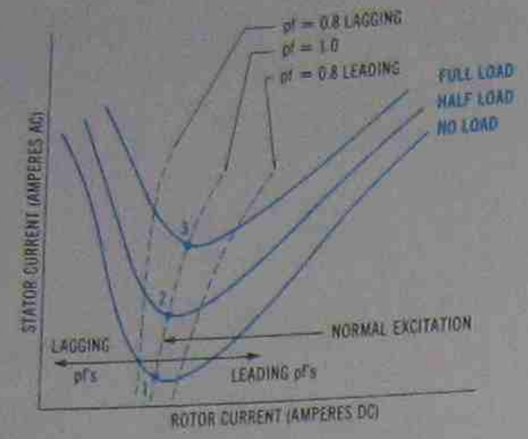
An outstanding advantage of the three-phase synchronous motor is that it can be connected to a three-phase power system to increase the overall power factor of the system. Power factor correction was discussed previously. Three-phase synchronous motors are sometimes used only to correct the system power factor. If no load is intended to be connected to the shaft of a three-phase synchronous motor, it is called a *synchronous capacitor*. It is designed to act only as a power factor corrective machine. Of course, it might be beneficial to use this motor as a constant-speed drive connected to a load, as well as for power factor correction.

We know from previous discussions that a low power factor cannot be tolerated by an electrical power system. Thus, the expense of installing three-phase synchronous machines could be justified by industries, in order to appreciably increase the system power factor. To understand how a three-phase synchronous machine operates as a power factor corrective machine, refer to the curves of Fig. 14-35. We know that the synchronous motor operates at a constant speed. Variation in rotor dc-excitation current has no effect on speed. The excitation level will change the power factor at which the machine operates. Three operational conditions may exist, depending on the amount of dc excitation applied to the rotor. These conditions are:

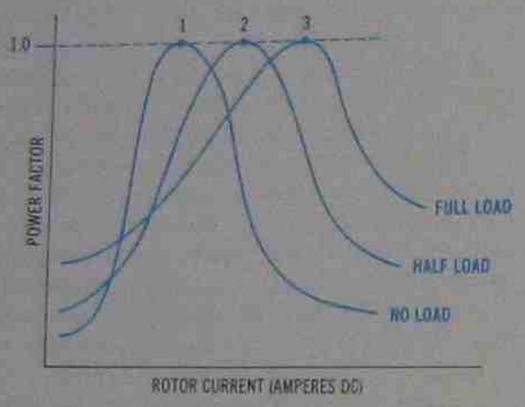


(A) Auxiliary-machine method. (B) Damper-windings-on-rotor method.

Fig. 14-34. Three-phase synchronous motor starting methods.



(A) Rotor current versus stator current.



(B) Rotor current versus power factor.

Fig. 14-35. Power relationships of a three-phase synchronous motor.

1. Normal excitation—operates at a power factor of 1.0.
2. Under excitation—operates at a lagging power factor (inductive effect).
3. Over excitation—operates at a leading power factor (capacitive effect).

Note the variation of stator current drawn by the synchronous motor as the rotor current varies. You should also see that stator current is minimum when the power factor equals 1.0, or 100%. The situations shown on the graph in Fig. 14-35A indicate stator and rotor currents under no-load, half-load, and full-load conditions. Current values when the power factors are equal to 1.0, 0.8-leading, and 0.8-lagging conditions are also shown. These curves are sometimes referred to as *V-curves* for a synchronous machine. The graph in Fig. 14-35B shows the variation of power factor with changes in rotor current under three different load conditions. Thus, a three-phase synchronous motor, when over-excited, can improve the overall power factor of a three-phase system.

As the load increases, the angle between the stator pole and the corresponding rotor pole on the synchronous machine increases. The stator current will also increase. However, the motor will remain synchronized unless the load causes "pull-out" to take place. The motor would then stop rotating due to the excessive torque required to rotate the load. Most synchronous motors are rated greater than 100 horsepower and are used for many industrial applications requiring constant-speed drives.

Wound-Rotor Induction Motor

The wound-rotor induction motor (wrim), shown in Fig. 14-36, is a specialized type of three-phase motor. This motor may be controlled externally by placing resistances in series with its rotor circuit. The starting torque of a wrim motor can be varied by the value of external resistance. The advantages of this type of motor are a lower starting current, a high starting torque, smooth acceleration, and ease of control. The major disadvantage of this type of motor is that it costs a great deal more than an equivalent three-phase induction motor using a squirrel-cage rotor. Thus, they are not used as extensively as other three-phase motors.

SPECIALIZED MECHANICAL POWER SYSTEMS

There is a need for specialized mechanical systems that can produce a rotary motion that is somewhat different from that produced by most electric motors. This type of system employs rotary motion to control the angular position of a shaft which is used to position the shaft of a second device. Synchro systems and servomechanisms are used to achieve this basic operation. With these devices, it becomes possible to transmit a rotary motion between locations without any direct mechanical linkage.

Synchro systems are classified as two or more motor/generator units connected together in a way that permits the transmission of angular shaft positions by electromagnetic field changes. When an operator turns the generator shaft of a unit to a certain position, it causes the motor shaft at a remote location to automatically rotate to an equivalent position. Using this type of system, it is possible to achieve accurate control of devices over long distances. Computers often employ these units to determine the physical changes that take place in automated operations.

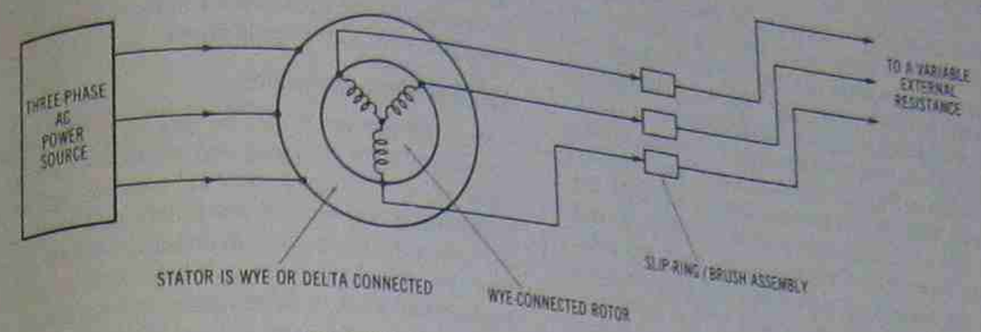


Fig. 14-36. Diagram of a wound-rotor induction motor.

In synchro systems that require increased rotational torque or precise movements of a control device, servomechanisms are employed. A servomechanism is ordinarily a special type of ac or dc motor that drives a precision piece of equipment in specific increments. Systems that include servomechanisms generally require amplifiers and error-detecting devices to control the angular displacement of a shaft.

Synchro System Operation

A synchro system contains two or more electromagnetic devices that are similar in appearance to small electric motors. These devices are connected together in such a way that the angular position of the generator shaft can easily be transmitted to the motor or receiver unit. Fig. 14-37 shows the schematic diagram of a basic synchro unit. As a general rule, the generator and motor units are identical electrically. Physically, the motor unit has a metal flywheel attached to its shaft to prevent shaft oscillations or vibrations when it is powered. The letters G or M inside of the electrical symbol denotes generator or motor functions.

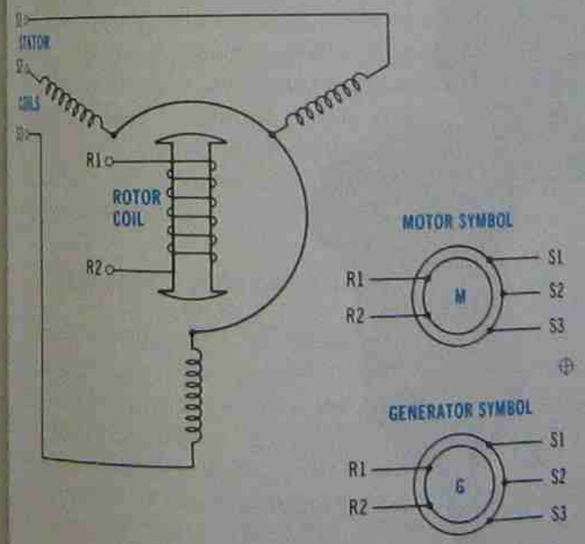


Fig. 14-37. Schematic diagram and symbols for a basic synchro unit.

Fig. 14-38 shows the circuit diagram of a basic synchro system. Single-phase ac line voltage is used to power this system. Note that the line voltage is applied to the rotors of both the generator and motor. The stationary coils, or stator windings, are connected together as indicated. When power is initially applied to the system, the motor will position itself according to the location of the generator shaft. No physical change will take place after the motor unit aligns itself with the generator position. Both units will remain in a stationary condition until some further action takes place. Turning the generator shaft a certain number of degrees in a clockwise direction will cause a corresponding change in the motor unit. If calibrated dials were attached to the shaft of each unit, they would show the same angular displacement change.

Fig. 14-39 shows a basic synchro unit disassembled. The stator coils are wound inside a cylindrical laminated metal housing. The coils are uniformly placed in slots and connected to provide three poles spaced 120° apart. These coils serve as the secondary windings of a transformer. The rotor coil of the synchro unit of Fig. 14-39 is also wound on a laminated core. This

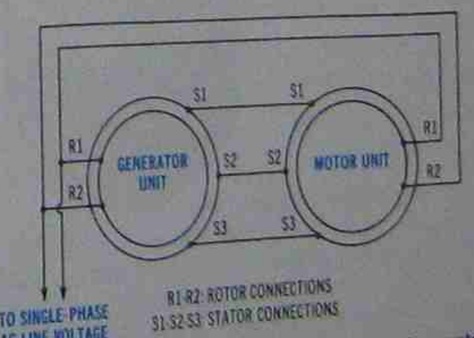


Fig. 14-38. Circuit diagram of a basic synchro system.

type of construction causes north and south poles of the magnetic field to extend from the laminated area of the rotor. Insulated slip rings on the shaft are used to supply ac power to the rotor. The rotor coil responds as the primary winding of a transformer.

When ac is applied to the rotor coil of the synchro unit shown in Fig. 14-37, it produces an alternating magnetic field. By transformer action, this field cuts across the stator coils and induces a voltage in each winding. The physical position of the rotor coil determines the amount of voltage induced in each stator coil. If the rotor coils are parallel with a stator coil, maximum voltage will be induced. The induced voltage will be of a minimum value when the rotor coils are at right angles to a stator-coil set.

The stator coils of the generator and motor of a synchro system are connected together as indicated in the circuit diagram of Fig. 14-38. Voltage induced in the stator coils of the generator, therefore, causes a resulting current flow in the stator coils of the motor. This, in turn, causes a corresponding magnetic field to be established in the stator of the motor. Line voltage applied to the rotor of the motor unit will cause it to align itself with the magnetic field of the stator coils.

Any change in rotor position of the generator unit is translated into an induced voltage and applied to the stator coils of the motor. Through this action, linear displacement changes can be effectively transmitted to the motor through three rather small stator coil wires. Systems of this type are becoming very important today in remote-control applications and in industrial automatic process-control applications.

Servo System Operation

Servo systems are a specific type of rotating machine used typically for changing the mechanical position or speed of a device. Mechanical-position applications include numerical-control machinery and process-control indicating equipment in industry. Speed applications are found in conveyor-belt control units, in spindle-speed control in machine-tool operations, and in disk or magnetic-tape drives for computers. As a general rule, a servo system is a rather complex unit that follows the commands of a closed-loop control path. Fig. 14-40 shows the components of a typical servo system.

The input of a servo system serves as the reference source or as a set point to which the load element responds. By changing the input in some way, a command is applied to the error detector. This device receives data from both the input source and from the controlled output device. If a correction is needed, with reference to the input command, it is amplified and applied to the actuator. The actuator is normally a servomotor that produces controlled shaft displacements. The controlled output device is usually a synchro

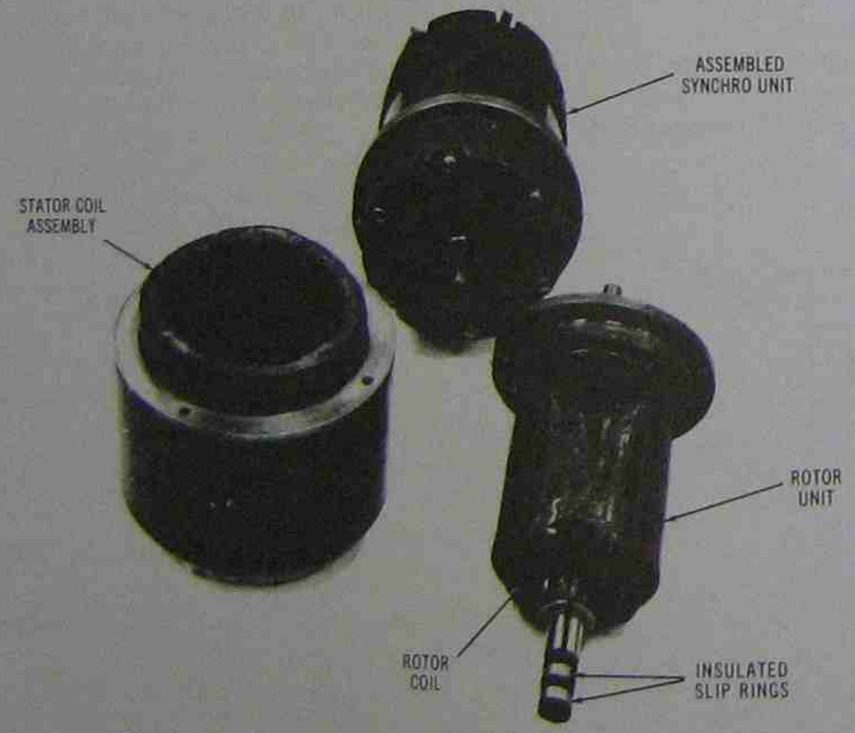


Fig. 14-39. Views of a synchro unit, assembled and disassembled.

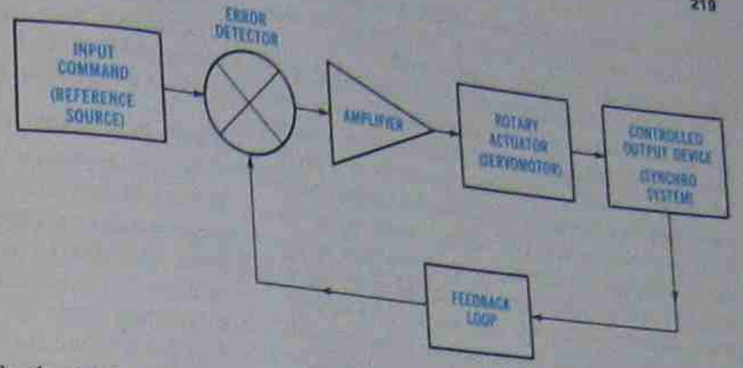


Fig. 14-40. Block diagram of a typical servo system.

system that relays information back to the error detector for position comparison.

A servomotor is primarily responsible for producing mechanical changes from an electromagnetic actuating device. A device of this type is normally coupled to the work load by a gear train or some mechanical linkage. Both ac and dc servomotors are used to achieve this operation. As a general rule, a servomotor is unique when compared with other electric motors because a servomotor is a very special type of device that is used to achieve a precise degree of rotary motion. Servomotors, for example, are designed to do something other than change electrical energy into rotating mechanical energy. Motors of this type must first be able to respond accurately to signals developed by the amplifier of the system. Secondly, they must be capable of reversing direction quickly when a specific signal polarity is applied. Also, the amount of torque developed by a servomotor must be quite high. As a general rule, the torque developed is a function of the voltage and current source.

Of the two distinct types of servomotors in use today, an ac type of motor, called a *synchronous* motor, is commonly used in low-power applications. Excessive amounts of heat developed during starting conditions normally limit this motor to rather low output-power applications. Direct-current stepping motors are also used as servomotors.

ELECTRIC MOTOR APPLICATIONS

Certain factors must be considered when selecting an electric motor for a specific application. Among these considerations are (1) the source voltage and power capability available, (2) the effect of the power factor and efficiency of the motor on the overall system, (3) the effect of the starting current of the motor on the system, (4) the effect of the power system on the operation of the motor, (5) the type of mechanical load, and (6) the expected maintenance it will require.

Motor Performance

The major consumer of electrical power is the electric motor. It is estimated that electric motors are responsible for 50% of the electrical power consumed in industrial usage and that 35% of all the electrical power used is used by electrical motors. For these reasons, we must consider the efficient operation of motors as a major part of our energy conservation efforts.

Both efficiency and the power factor must be considered in determining the effect of a motor in terms of efficient power conversion. Remember the following relationships. First,

$$\text{Efficiency}\ (\%) = \frac{P_{out}}{P_{in}} \times 100$$

where,

P_{in} is the power input in horsepower,
P_{out} is the power output in watts.

(To convert horsepower to watts, remember that 1 horsepower = 746 watts.) Then,

$$pf = \frac{P}{VA}$$

where,

pf is the power factor of the circuit,
P is the true power in watts,
VA is the apparent power in voltamperes.

The maximum pf value is 1.0, or 100%, which would be obtained in a purely resistive circuit. This is referred to as *unity power factor*.

Effect of Load

Since electrical power will probably become more expensive and less abundant, the efficiency and power factor of electric motors will become increasingly more important. The efficiency of a motor shows mathematically just how well a motor converts electrical energy into mechanical energy. A mechanical load placed on

a motor affects its efficiency. Thus, it is particularly important for industrial users to load motors so that their maximum efficiency is maintained.

Power factor is also affected by the mechanical load placed on a motor. A higher power factor means that a motor requires less current to produce a given amount of torque or mechanical energy. Lower current levels mean that less energy is being wasted (converted to heat) in the equipment and circuits connected to the motor. Penalties are assessed on industrial users by the electrical utility companies for having low system power factors (usually less than 0.8 or 0.85 values). By operating at higher power factors, industrial users can save money on penalties and help, on a larger scale, with more efficient utilization of electrical power. Motor load affects the power factor to a much greater extent than it does the efficiency. Therefore, motor applications should be carefully studied to assure that motors (particularly very large ones) are not overloaded or underloaded, so that the available electrical power will be used more effectively.

Effect of Voltage Variations

Voltage variation also has an effect on the power factor and efficiency. Even slight changes in voltage produce a distinct effect on the power factor. However, a less distinct effect results when the voltage causes a variation in the efficiency. As proper power utilization is becoming more and more important, motor users should make sure that their motors do not operate at undervoltage or overvoltage conditions.

PROBLEMS

1. A shunt-wound dc motor converts 3000 watts of electrical power when connected to a 120-volt dc source. Its field resistance is 85 ohms. Find: (A) line current, (B) field current, and (C) armature current.
2. A shunt-wound dc motor draws 40 amperes of current from a 120-volt source. It has a field resistance of 30 ohms and an armature resistance of 1 ohm. Find: (A) field current, (B) armature current, (C) cemf, and (D) total power.
3. What is the horsepower of a motor running at 3450 revolutions per minute that has a torque of 35 foot-pounds?
4. The no-load speed of an induction motor is 1790 revolutions per minute and the full-load speed is 1725 revolutions per minute. What is its speed regulation?
5. What is the slip (%) of the motor given in Problem 4?
6. What is the rotor frequency of the motor given in Problem 4?
7. What is the synchronous speed of a 12-pole 60-Hz *three-phase* ac motor?
8. What is the synchronous speed of a 12-pole 60-Hz *single-phase* ac motor?
9. A 120-volt dc motor develops a cemf of 105 volts. Its armature resistance is 0.75 ohms. What is its armature current?
10. A three-phase synchronous capacitor rated at a 0.8 power factor (leading) is connected across a 240-volt three-phase power line. The power factor of the system prior to connection of the synchronous machine was 0.7 (lagging). What effect (increase or decrease) will the addition of the synchronous capacitor have on the following factors of the three-phase system: (a) power factor, (b) line current, (c) apparent power, and (d) reactive power?
11. When the mechanical load applied to the shaft of an induction motor increases, what effect on the following operational factors results: (a) speed, (b) line current, (c) power factor, (d) efficiency, (e) torque, and (f) horsepower?

UNIT V

Power Measurement

In order to understand electrical power measurement systems, we must first study the fundamentals of measurement. These fundamentals deal mainly with the characteristics and types of measurement systems. They are discussed in Chapter 15. Then, Chapter 16 deals with the specialized measurement methods associated with electrical power systems. These measurement systems include single-phase and three-phase wattmeters, power factor meters, ground-fault indicators, and telemetering systems.

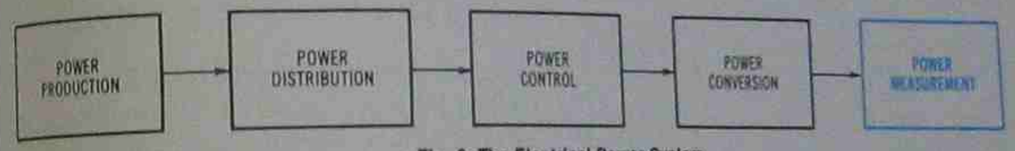


Fig. 5. The Electrical Power System.

CHAPTER 15

Measurement Fundamentals

Electrical quantities, power-related quantities, and physical quantities are important values which must be measured. Electrical power systems are dependent upon accurate measurements for everyday operation. Thus, many types of measurements and measuring equipment are associated with electrical power systems. Measurement fundamentals will be discussed in the following sections.

Today, most nations of the world use the metric system of measurement. In the United States, the National Bureau of Standards began a study in 1968 to determine the feasibility and costs of converting the nation to the metric measurement system. Today, this conversion is taking place.

The units of the metric system are decimal measures based on the kilogram and the meter. Although the metric system is very simple, several countries have been slow to adopt it. The United States has been one of these reluctant countries due to the complexity of actions required by a complete changeover of measurement systems.

MEASUREMENT QUANTITIES

Most measurement is based on the International System of Units (SI). The basic units of this system are the meter, kilogram, second, and ampere (MKSA). These are the units of length, mass, time, and electrical current. Other systems, such as the meter-kilogram-second (MKS) and the centimeter-gram-second (CGS) recognize only three base units. However, these two systems are closely associated with the metric system.

There are several derived units that are used extensively for electrical and other related measurements. The electrical units that we now use are part of the International System of Units (SI) and are based on the meter-kilogram-second-ampere (MKSA) system. The International System of Derived Units is shown in Table 15-1.

Table 15-1. International System of Derived Units

Measurement Quantity	SI Unit
Area	square meter
Volume	cubic meter
Frequency	hertz
Density	kilogram per cubic meter
Velocity	meter per second
Acceleration	meter per second per second
Force	newton
Pressure	pascal (newton per square meter)
Work (energy), quantity of heat	joule
Power (mechanical, electrical)	watt
Electrical charge	coulomb
Permeability	henry per meter
Permittivity	farad per meter
Voltage, potential difference, electromotive force	volt
Electric flux density, displacement	coulomb per square meter
Electric field strength	volt per meter
Resistance	ohm
Capacitance	farad
Inductance	henry
Magnetic flux	weber
Magnetic flux density (magnetic induction)	tesla
Magnetic field strength (magnetic intensity)	ampere per meter
Magnetomotive force	ampere
Magnetic permeability	henry per meter
Luminous flux	lumen
Luminance	candela per square meter
Illumination	lux

CONVERSION OF SI UNITS

Sometimes it is necessary to make conversions of SI units so that very large or very small numbers may be avoided. For this reason, decimal multiples and

submultiples of the basic units have been developed by using standard prefixes. These standard prefixes are shown in Table 15-2. As an example, we may express 1000 volts as 1 kilovolt or 0.001 ampere as 1 milliampere. A chart is given in Fig. 15-1 that shows the relationship of these prefixes. Since the United States

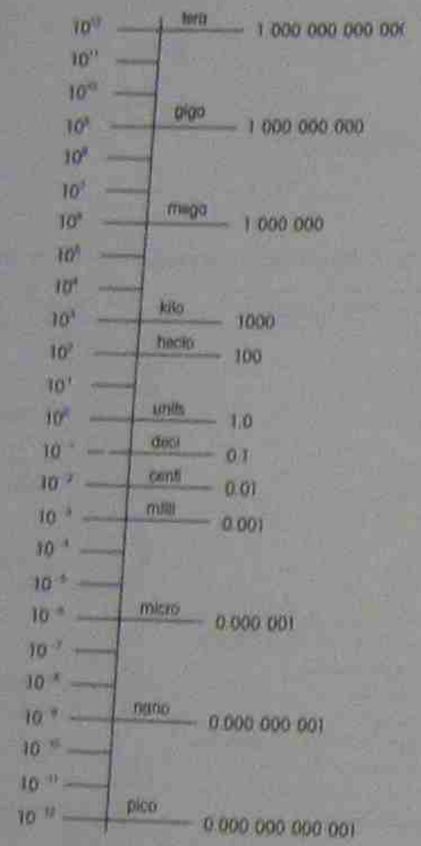


Fig. 15-1. Conversion chart for large and small numbers.

is in the process of converting from the English system of measurement to the Systems International (metric) system, you should be familiar with the conversion factors. These are shown in Appendix C.

BASICS OF MEASUREMENT SYSTEMS

All measurement systems have certain basic characteristics. Usually a specific quantity is monitored either periodically or continuously. Therefore, some type of visual indication must be available of the quantity being monitored. For this purpose, several types of instruments for measuring electrical and physical quantities are available. The basic types of measurement systems can be classified as: (1) hand-deflection instruments, (2) comparative instruments, (3) cathode-ray tube (crt) display instruments, (4) numerical-readout instruments, and (5) chart-recording instruments.

Table 15-2. SI Standard Prefixes

Prefix	Symbol	Factor by Which the Unit is Multiplied
exa	E	1,000,000,000,000,000,000 = 10^{18}
peta	P	1,000,000,000,000,000 = 10^{15}
tera	T	1,000,000,000,000 = 10^{12}
giga	G	1,000,000,000 = 10^{9}
mega	M	1,000,000 = 10^{6}
kilo	k	1,000 = 10^{3}
hecto	h	100 = 10^{2}
deka	da	10 = 10^{1}
deci	d	0.1 = 10^{-1}
centi	c	0.01 = 10^{-2}
milli	m	0.001 = 10^{-3}
micro	μ	0.000001 = 10^{-6}
nano	n	0.000000001 = 10^{-9}
pico	p	0.000000000001 = 10^{-12}
femto	f	0.000000000000001 = 10^{-15}
atto	a	0.000000000000000001 = 10^{-18}

Hand-Deflection Instruments

Instruments which rely upon the motion of a hand or pointer are referred to as hand-deflection instruments. The volt-ohm-milliammeter (vom) is one type of hand-deflection instrument. The vom is a multifunction, multirange meter (Fig. 15-2). Single function meters can also be used to measure electrical or physical quantities. The basic part of an electrical hand-deflection meter is called the *meter movement* and is shown in Figs. 15-3 and 15-4. The movement of the hand along a calibrated scale is used to indicate an electrical or physical quantity. Physical quantities such as air flow or fluid pressure can also be monitored by hand-deflection meters.

Many meters employ a hand-deflection movement called the D'Arsonval, or moving-coil, type. The basic operational principle of this type of movement is shown in Fig. 15-5. The hand or needle of the movement remains stationary on the left portion of the calibrated scale until a current flows through the electromagnetic coil that is centrally located within a permanent magnetic field. When current flows through the coil, a reaction between the electromagnetic field of the coil and the stationary permanent magnetic field is developed. This reaction causes the hand (pointer) to deflect toward the right portion of the scale. This basic moving-coil meter movement operates due to the same principle as an electric motor. It may be used for either single function meters, which measure only one quantity, or for multifunction meters, such as a transistorized voltmeter (tvm) or a vacuum-tube voltmeter (vtvm). See Figs. 15-6 and 15-7. The basic meter movement may be modified so that it will measure almost any electrical or physical quantities.

Courtesy Triplett Corp.

Fig. 15-2. A volt-ohm-milliammeter (vom).

Comparative Instruments

There is another group of measuring instruments that can be classified as comparative instruments. Usually, a comparative instrument is designed to compare a component of a known value to some unknown value. The accuracy of a comparative instrument is ordinarily much better than that of a hand-deflection instrument.

A Wheatstone bridge, such as is shown in Fig. 15-8, is a typical type of comparative instrument. The technique used for measurement with a Wheatstone bridge is illustrated in Fig. 15-9. A voltage source is used in conjunction with a resistive bridge circuit, and a sensitive zero-centered moving-coil meter movement. The

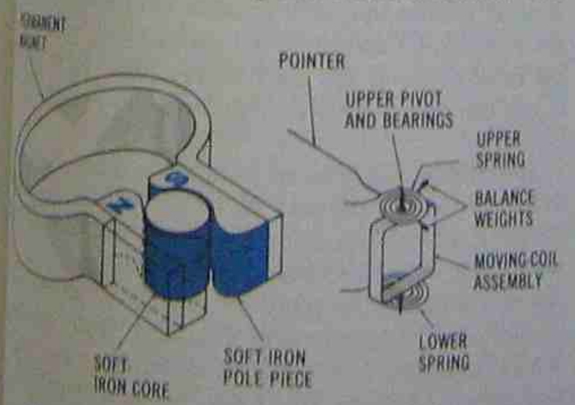


Fig. 15-3. Construction details of a meter movement.

Fig. 15-4. Photograph of a meter movement.

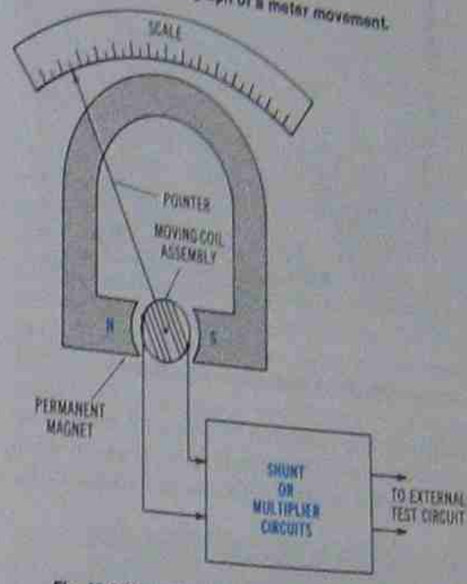
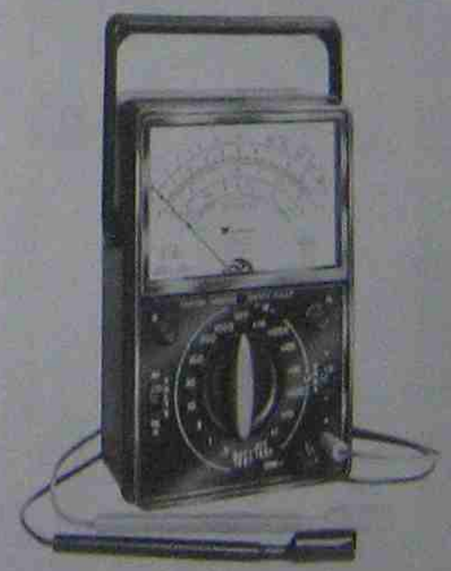
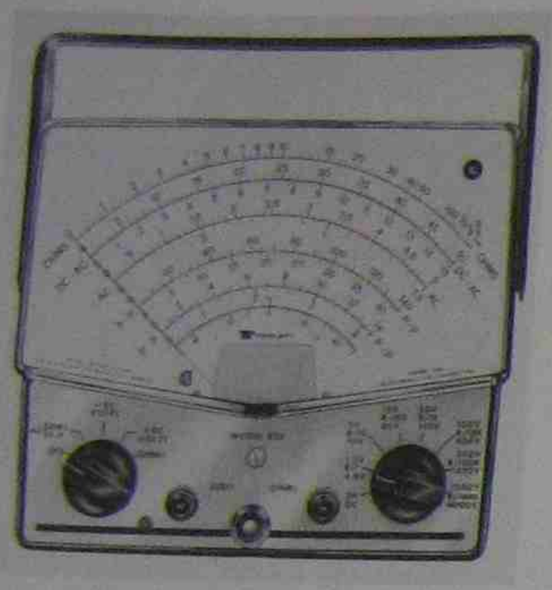


Fig. 15-5. Operating principle of a meter movement.



Courtesy Triplett Corp.

Fig. 15-6. A transistorized voltmeter (tvm).



Courtesy Triplett Corp.

Fig. 15-7. A vacuum-tube voltmeter (vtvm).

bridge circuit is completed by adding the external unknown resistance (R_X) that is to be measured. When R_S is adjusted so that the resistive path formed by R_X and R_S is equal to the path formed by R_1 and R_2, no current will flow through the meter. In this condition, the meter will indicate zero (referred to as a *null*) and the bridge is said to be balanced. The value of standard resistance (R_S) is marked on the meter so that the value of the unknown resistance (R_X) can be determined.

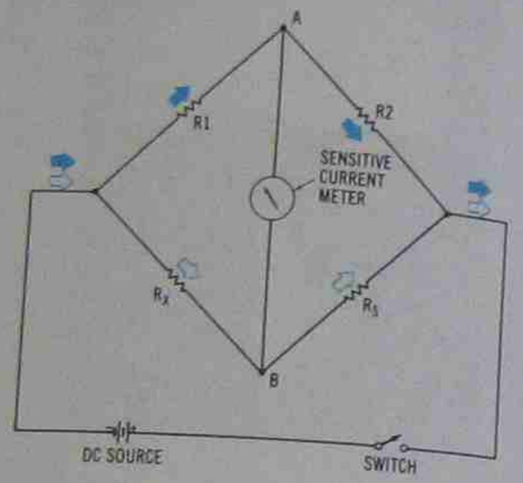


Fig. 15-9. Schematic diagram of a Wheatstone bridge circuit.

Resistors R_1 and R_2 form the "ratio arm" of the indicator. The value of an unknown resistance (R_X) may be mathematically expressed as:

$$R_X = \frac{R_1}{R_2} \times R_S.$$

The Wheatstone bridge will measure most values of resistance with considerable accuracy. Several other types of comparative instruments also use the Wheatstone bridge principle.

Courtesy Leeds & Northrup Co.

Fig. 15-8. A Wheatstone bridge.

Cathode-Ray Tube (CRT) Display

A cathode-ray tube display instrument, usually called an oscilloscope, is an important type of instrument. By using an oscilloscope, it is possible to visually monitor the voltages of a system. The basic operational part of the oscilloscope is the cathode-ray tube. Fig. 15-10 shows the construction and electron-gun arrangement of a crt.

Several different types of crt display instruments are available. General-purpose oscilloscopes are used for electronic servicing and for displaying simple types of waveforms. Triggered-sweep oscilloscopes are used where it is desired to apply an external voltage to the oscilloscope for comparative purposes. Other oscilloscopes, classified as laboratory types, have very high sensitivity and good frequency response over wide ranges. A crt display instrument may be used to mea-

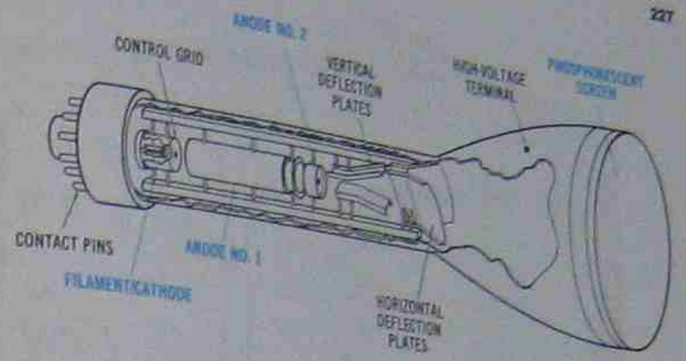


Fig. 15-10. Construction of a cathode-ray tube.

sure ac and dc voltages, frequency and phase relationships, and various timing and numerical-control applications. Memory and storage-type instruments are available for use for more sophisticated measurement purposes.

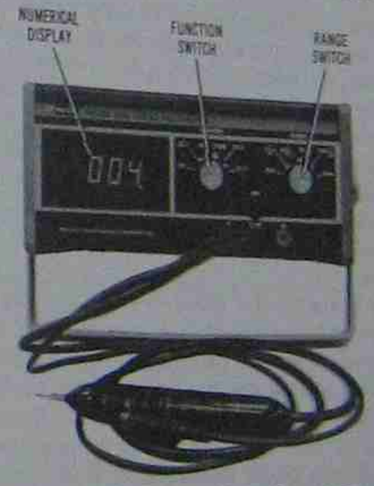
Numerical-Readout Instruments

Many modern instruments employ numerical readouts. These simplify the measurement processes and permit making more accurate measurements. Numerical-readout instruments, such as the one shown in Fig. 15-11, rely upon the operation of digital circuitry in order to produce a numerical display of the measured quantity.

Chart-Recording Instruments

The types of instruments discussed previously are used when no permanent record of the measured quantity values is needed. However, instruments can be employed that provide a permanent record of the quantity values. Also, values that are measured over a specific time period can be recorded. A chart-recording instrument, as shown in Fig. 15-12, is such a machine. The types of chart recorders include both pen and ink recorders and inkless recorders.

Pen and ink recorders have a pen attached to the instrument. This pen is caused by either electrical or mechanical means to touch a paper chart and leave a permanent record of the measured quantity on the chart. The charts utilized may be either roll charts (which revolve on rollers under the pen mechanism) or circular charts (which revolve on an axis under the pen). Chart recorders may use more than one pen, if desired, to record several quantities simultaneously. In this case, each pen mechanism would be connected to measure a specific quantity. The pen of a chart recorder is a capillary tube device that is actually an extension of the basic meter movement. The pen must be connected to a constant source of ink. The pen is moved by the torque that is exerted by the meter movement just as the pointer of a hand-deflection type of meter is moved. The chart used for recording the measured quantity usually contains lines that correspond to the radius of the pen movement. Increments on the chart are marked according to time intervals. The chart must be moved under the pen at a constant speed. Either a spring-drive mechanism, a synchronous ac motor, or a dc servomotor can be used to drive the



Courtesy Dynascan Corp.

Fig. 15-11. A numerical-readout instrument.

chart. Recorders are also available which use a single pen to make permanent records of measured quantities on a single chart. In this case, either coded lines or different colored ink could be used to record the quantities.

Inkless recorders may use a voltage applied to the pen point to produce an impression on a sensitive paper chart. In another process, the pen is heated to cause a trace to be melted along the chart paper. The obvious advantage of inkless recorders is that ink is not required.

Fig. 15-12. A chart-recording instrument. Courtesy Gould, Inc.

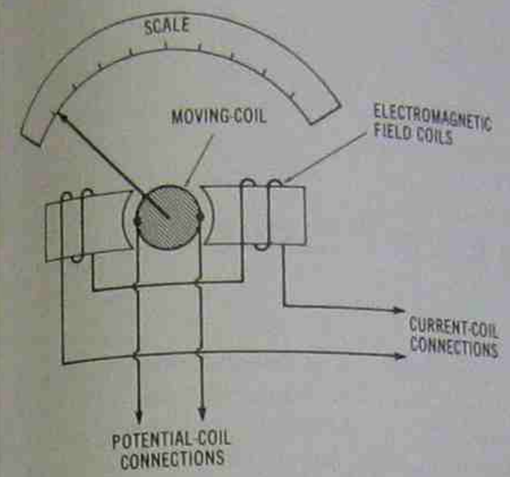
Chart-recording instruments are commercially available for measuring almost any electrical or physical quantity. For many applications, the recording system may be located a great distance from the device being measured. For accurate system monitoring, a central instrumentation system might be used. Power plants, for instance, ordinarily use chart recorders at a centralized location to monitor the various electrical and physical quantities involved in the power-plant operation.

The operation of a typical roll-chart recording instrument involves several basic principles. The user should assure that the chart roll has enough paper to last throughout the duration of the time that it is to be used. The ink supply should be checked. If ink is needed, the well should be filled to the proper level. Also, the pen should be checked for proper pressure on the roll chart and for accurate adjustment along the incremental scale of the roll chart. The user should also assure that the meter is properly connected to the external circuit (that is needed for making the desired measurement).

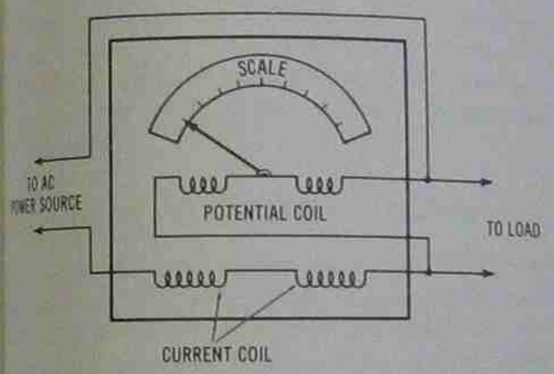
MEASURING ELECTRICAL POWER

Electrical power is measured with a wattmeter. A meter movement called a *dynamometer movement*, shown in Fig. 15-13, is used for most wattmeters. Note that this movement has two electromagnetic coils. One coil, called the *current* coil, is connected in series with the load to be measured. The other coil, called the *potential* coil, is connected in parallel with the load. Thus, the strength of each electromagnetic field affects the movement of the meter pointer. The operating principle of this movement is similar to that of the moving-coil type, except that there is a fixed electromagnetic field rather than a permanent-magnet field.

When measuring dc power, the total power is the product of voltage times current ($P = V \times I$). However, when measuring ac power, we must consider the power factor of the load, since $P = V \times I \times pf$. The true power of an ac circuit may be read directly with a wattmeter. When a load is either inductive or capacitive, the true power will be less than the apparent power ($V \times I$).



(A) Basic dynamometer movement.



(B) Wattmeter movement using dynamometer movement.

Fig. 15-13. Measuring electrical power.

1. Use the conversion factors given in Table 15-2 and Fig. 15-1 to convert the following electrical units.

a. 0.6 volt = _____ millivolt(s).
b. 0.005 volt = _____ microvolt(s).
c. 0.28 volt = _____ millivolt(s).
d. 0.058 ampere = _____ milliampere(s).
e. 0.000052 ampere = _____ microampere(s).
f. 0.582 watt = _____ milliwatt(s).
g. 15 nanoamperes = _____ ampere(s).
h. 152 microwatts = _____ watt(s).
i. 560 milliwatts = _____ watt(s).
j. 68 milliamperes = _____ ampere(s).
k. 5200 ohms = _____ kilohm(s).
l. 0.85 megohms = _____ ohm(s).
m. 18 kilowatts = _____ watt(s).
n. 3,500,000 watts = _____ megawatt(s).
o. 6.5 kilowatts = _____ watt(s).

2. Refer to the metric conversion charts in Appendix C to make the following unit conversions.

a. 12 inches = _____ centimeter(s).
b. 5 yards = _____ meter(s).
c. 50 millimeters = _____ inch(es).
d. 59 kilometers = _____ meter(s).
e. 18 square inches = _____ square centimeter(s).
f. 61 square miles = _____ square kilometer(s).
g. 32 square centimeters = _____ square inch(es).
h. 16 ounces = _____ grams.
i. 8 pounds = _____ kilograms.
j. 31 kilograms = _____ pounds.
k. 620 milliliters = _____ fluid ounces.
l. 13 liters = _____ quarts.
m. 85 gallons = _____ liters.
n. 4 cups = _____ liter(s).
o. 0.5 cubic meters = _____ cubic feet.
p. 18 cubic yards = _____ cubic meters.
q. 35 cubic feet = _____ liters.
r. 0.5 gallon = _____ cubic inches.
s. 55 Btu/min = _____ horsepower.
t. 0.25 horsepower = _____ watt.
u. 15 kilowatts = _____ horsepower.
v. 3 degrees C. = _____ degrees F.
w. 57 degrees F. = _____ degrees C.
x. 81 degrees C. = _____ degrees R.
y. −40 degrees C. = _____ K.

3. Express the following numbers as powers of ten:

a. 0.00001
b. 0.00000001
c. 10,000,000
d. 1000
e. 10
f. 0.01
g. 10,000
h. 0.0001
i. 1.0

4. Express the following numbers in scientific notation:

a. 0.00128
b. 1520
c. 0.000632
d. 0.0030
e. 28.2
f. 7,300,000,000

CHAPTER 16

Specialized Testing and Measurement Devices

The day-to-day operation of homes, businesses, and industries relies upon the use of electrical power. In order to use power more effectively, electrical power use should be monitored. Several types of electrical power measurement applications utilize meters to measure electrical power and its related factors. In the following sections, we will discuss the measurement of electrical power and some related types of measurement checks. These measurement tests are important in assuring the most efficient operation of electrical power systems.

MEASURING ELECTRICAL ENERGY

In Chapter 15, basic measurement of electrical power was described. Wattmeters using dynamometer movements, that monitor both voltage and current in a circuit, are ordinarily used to measure the electrical power that is converted by the load of a power system. For instance, the amount of electrical energy converted into mechanical energy by a motor can be measured by properly connecting a wattmeter to the motor circuit.

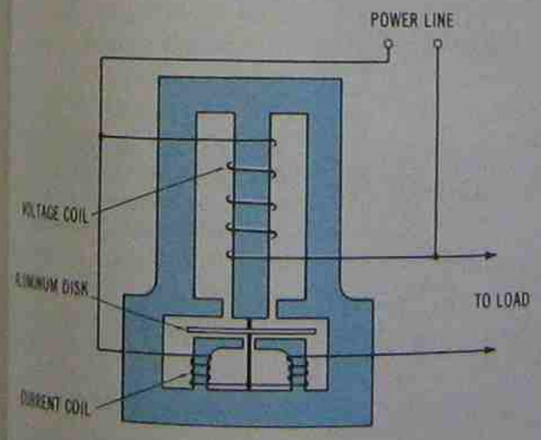


Fig. 16-1. Construction diagram of a watt-hour meter.

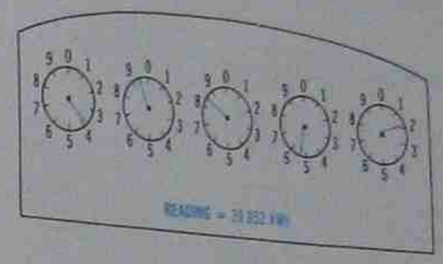


Fig. 16-2. Registering dials of a watt-hour meter.

Recall that the power factor of the load must be considered when measuring electrical power.

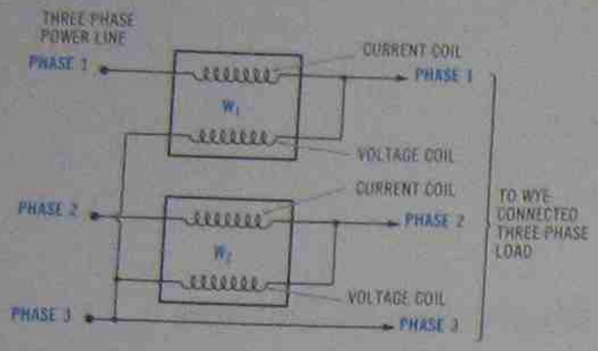
Watt-Hour Meters

The amount of electrical energy used over a certain period of time may be measured by using a watt-hour meter. A watt-hour meter, illustrated in Fig. 16-1, relies upon the operation of a small motor mounted inside its enclosure. The speed of the motor is proportional to the power applied to it. The rotor is an aluminum disk that is connected to a numerical register, which usually indicates the number of kilowatt-hours of electrical energy used. Fig. 16-2 shows the dial-type face plate that is frequently used on watt-hour meters. Other types of watt-hour meters have a direct numerical readout of the kilowatt-hours used.

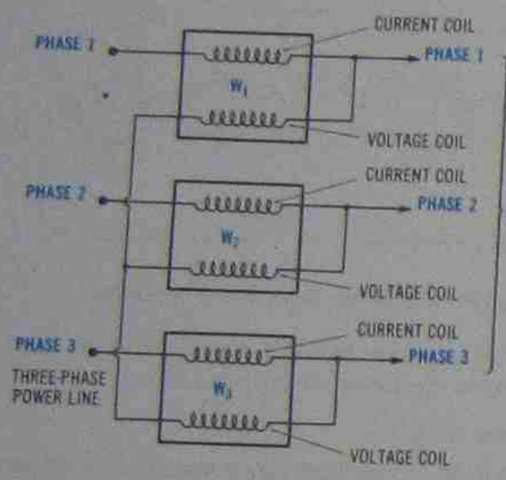
The watt-hour meter is connected between the incoming power lines and the branch circuits of an electrical power system. In this way, all electrical energy that is used must pass through a kilowatt-hour meter. The same type of system is used for home, industrial, or commercial service entrances.

Meter Operation

The electrical operation of a watt-hour meter is in many ways similar to the conventional wattmeter. A potential coil is connected across the incoming power lines to monitor voltage while a current meter is placed in series with the line to measure current. Both meter



(A) Two-wattmeter method.



(B) Three-wattmeter method.

Fig. 16-3. Using single-phase wattmeters to measure three-phase power.

sections are contained within the watt-hour meter enclosure. The voltage and current of the power system affect the movement of an aluminum-disk rotor which is part of the watt-hour meter assembly. The operation of the watt-hour meter may be considered as similar to an ac induction motor. The stator is an electromagnet that has two sets of windings—the voltage windings and the current windings. The field developed in the voltage windings causes a current to be induced into the aluminum disk. The torque produced is proportional to the voltage and the *in-phase* current of the system. Therefore, the watt-hour meter will monitor the true power converted in a system.

MEASURING THREE-PHASE ELECTRICAL ENERGY

For industrial and commercial applications, it is usually necessary to monitor the three-phase energy that is utilized. It is possible to use a combination of single-phase wattmeters to measure the total three-phase power, as shown in Fig. 16-3. The methods shown are ordinarily not very practical since the sum of the meter readings would have to be found in order to calculate the total power of a three-phase system.

Three-phase wattmeters, as shown in Fig. 16-4, are designed to monitor the true power of a three-phase system by using one meter. The torque developed to rotate the movement is dependent upon the voltage and current of the three phases acting on the system. Three-phase watt-hour meters are available that use three aluminum disks on the same shaft to monitor the three-phase power converted by the system. The total

Courtesy Weston Instruments, Inc.

Fig. 16-4. An industrial analyzer that monitors true three-phase power, reactive power, line current, line voltage, and line frequency.

rque that rotates the shaft is, therefore, a combina- n of the torques developed by each phase. The total wer will be proportional to the total three-phase wer converted by the system.

Measuring Power Factor

We know that power factor is the ratio of the true wer of a system to the apparent power (volts × mperes). To determine power factor, we could use a ttmeter, voltmeter, and an ammeter and use the lationship of pf = W/VA. However, it would be more nvenient to use a power factor meter in situations ere the power factor must be monitored.

The principle of a power factor meter is shown in g. 16-5. The power factor meter is similar to a watt- ter, except that it has two armature coils that will ve due to their electromagnetic field strengths. The mature coils are mounted on the same shaft so that ir alignment is about 90° apart. One coil is connected ross the ac line (in series with a resistance) while e other coil is connected across the line through an sistance. The resistive path through the coil reacts produce a flux proportional to the *in-phase* compo- nt of the power. The inductive path reacts in pro- portion to the *out-of-phase* component of the power.

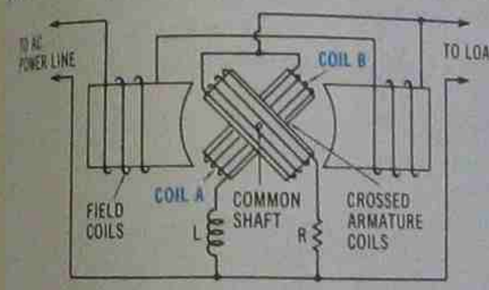


Fig. 16-5. Schematic diagram of a power factor meter circuit.

If a unity (1.0) power factor load is connected to e meter, the current in the resistive path through coil A would develop full torque. Since there is no out-of- ase component, no torque would be developed rough the inductive path. The meter movement would w indicate full-scale or unity power factor. As the wer factor decreases below 1.0, the torque developed the inductive path through coil B would become eater. This torque would be in opposition to the rque developed by the resistive path. Therefore, a wer factor of less than 1.0 would be indicated. The ale must be calibrated to measure power factor ranges om zero to unity.

Other Types of Measurement Devices

Various other types of instruments are commercially ailable for measuring three-phase power and other power-related quantities. Power-monitoring instruments which may be used for analysis of true three-phase power, reactive power, current, and voltage are sometimes referred to as *industrial analyzers* (Fig. 16-4). Such indicators usually have several instruments housed in a single enclosure. In this way, the related three-phase quantities may be observed easily to better understand how the power system of the industry is functioning.

The Power-Demand Factor

Fig. 16-6 shows a power-demand monitor. This instrument performs an important industrial function. Power demand is expressed as:

$$\text{power demand} = \frac{\text{peak power used (kW)}}{\text{average power used (kW)}}$$

This ratio is important since it indicates the amount above the average power consumption that a utility company must supply an industry. Power demand is usually calculated over a 15-, 30-, or 60-minute interval and, then, converted into longer periods of time.

Industries may be penalized by a utility company if their peak power demand far exceeds their average demand. Power-demand monitors help industries to better utilize their electrical power. A high peak demand means that the equipment for an industrial power-distribution system must be rated higher. The closer that the peak demand approaches the value of the average demand, the more efficient the industrial power system is in terms of power utilization.

FREQUENCY MEASUREMENT

Another power measurement that is very important is the frequency. The frequency of the power source must remain stable or the operation of many types of equipment can be affected. Frequency refers to the number of cycles of voltage or current which occur in a given period of time. The unit of measurement for frequency is the hertz (Hz), which means cycles per second. A table of frequency bands is shown in Fig. 16-7. The standard power frequency in the United States is 60 hertz. Some other countries use 50 hertz.

Frequency can be measured with several different types of meters. An electronic counter is one type of frequency indicator. Vibrating-reed instruments are also commonly used for measuring power frequencies (Fig. 16-8). An oscilloscope can also be used to measure frequency. Graphic recording instruments may be used to provide a visual display of frequency over a period of time. The electrical power industry uses this method to monitor the frequency output of its alternators.

Fig. 16-6. A power-demand monitor.

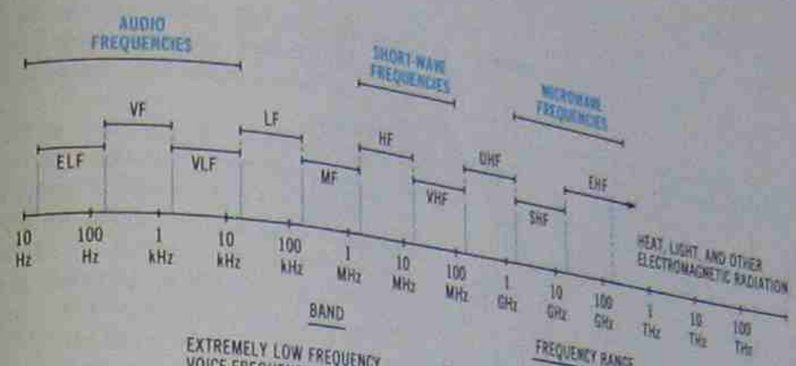
Courtesy Pacific Technology, Inc.

SYNCHROSCOPES

The major application for a synchroscope is in electrical power plants. Most power plants have more than one alternator. In order to connect two or more alternators onto the same ac line, the following conditions must be met: (1) their voltage outputs must be equal, (2) their frequencies must be equal, (3) their voltages must be in phase, and (4) the phase sequence of the voltages must be the same.

Voltage output levels may be checked easily with a voltmeter of the transformer-type that is used to monitor high voltages. Frequency is adjusted by varying the speed of an alternator and is also easy to monitor. The phase sequence is established on each alternator when it is installed and connected to the electrical power system. The additional factor, which must also be monitored before paralleling alternators, is to assure that the output voltages of both alternators are in phase. This is done by using a synchroscope (see Fig. 16-9).

A synchroscope is used to measure the relationship between the phases of the system and the alternator that is to be put in parallel or "on-line." A synchroscope also indicates whether the alternator is running faster or slower than the system to which it is being connected. The basic design of the indicator utilizes a phase-comparative network of two RLC circuits which are connected between the operating system and



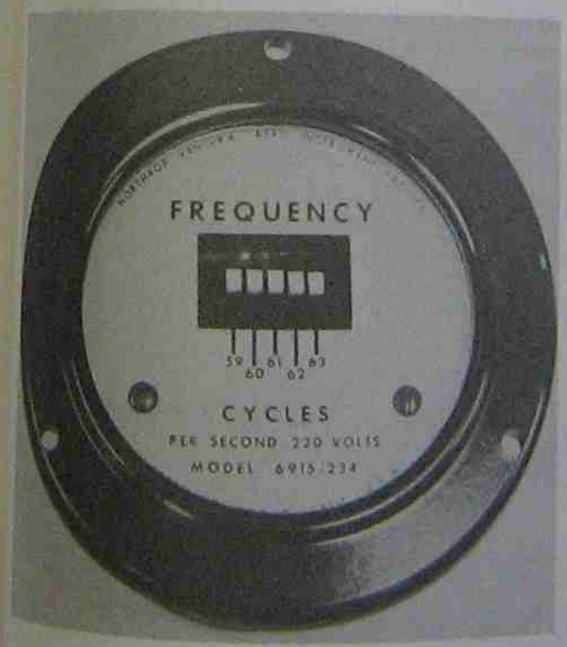
BAND		FREQUENCY RANGE
EXTREMELY LOW FREQUENCY	(ELF)	
VOICE FREQUENCY	(VF)	30 Hz TO 300 Hz
VERY-LOW FREQUENCY	(VLF)	300 Hz TO 3 kHz
LOW FREQUENCY	(LF)	3 kHz TO 30 kHz
MEDIUM FREQUENCY	(MF)	30 kHz TO 300 kHz
HIGH FREQUENCY	(HF)	300 kHz TO 3 MHz
VERY-HIGH FREQUENCY	(VHF)	3 MHz TO 30 MHz
ULTRA-HIGH FREQUENCY	(UHF)	30 MHz TO 300 MHz
SUPER-HIGH FREQUENCY	(SHF)	300 MHz TO 3 GHz
EXTREMELY HIGH FREQUENCY	(EHF)	3 GHz TO 30 GHz
		30 GHz TO 300 GHz

Fig. 16-7. Classification of frequency bands.

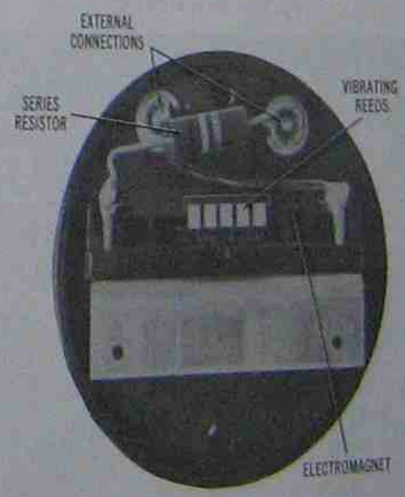
the alternator to be paralleled. The meter scale shows whether the new alternator is running too slow or too fast (see Fig. 16-9). When an in-phase relationship, along with the other three factors previously discussed exists, the alternator may be put "on-line" or connected in parallel with a system that is already operational. The addition of another alternator to the system will allow a higher power capacity to be produced by the electrical power system.

GROUND-FAULT INDICATORS

Ground-fault indicators are used to locate faulty system or equipment grounding conditions. The equip-

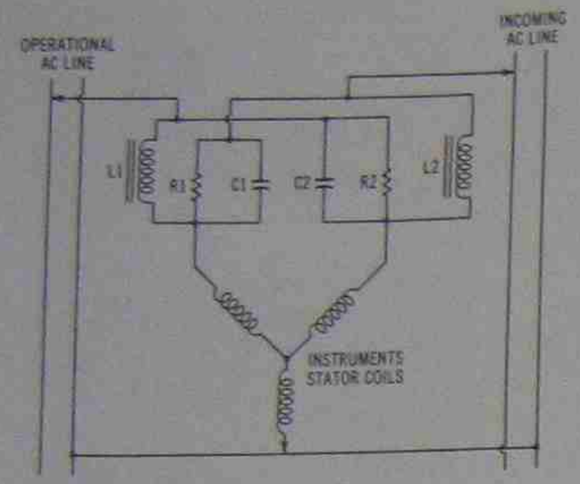


(A) External view.

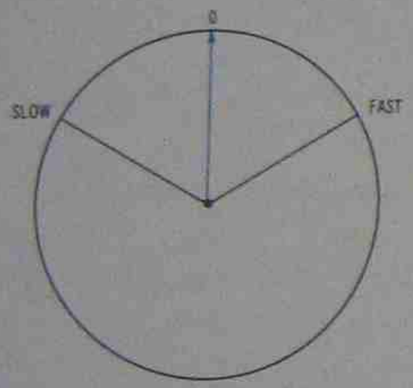


(B) Internal view.

Fig. 16-8. A vibrating-reed frequency indicator.



(A) Schematic diagram.



(B) Indicator scale.

Fig. 16-9. The synchroscope.

ment of electrical power systems must be properly grounded. Proper grounding procedures, principles, and ground-fault interrupters were discussed in Chapter 7.

A ground-fault indicator, such as the one shown in Fig. 16-10, may be used to check for faulty grounding at various points in an electrical power system. Several conditions can exist that might be hazardous. These faulty wiring methods include: (1) hot and neutral wires reversed, (2) open equipment ground wire, (3) open neutral wire, (4) open hot wire, (5) hot and equipment ground wires reversed, or (6) hot wire on the neutral terminal and the neutral is not connected. Each of these conditions would present a serious problem in the electrical power system. Although proper wiring eliminates most of these problems, a periodic check with a ground-fault indicator would assure that the electrical wiring is safe and efficient.

MEGOHMMETERS

A megohmmeter, such as the one shown in Fig. 16-11, is used to measure high resistances which are beyond the range of a typical ohmmeter. These indicators are used primarily for checking the quality of insulation on electrical power equipment (mainly motors). The quality of equipment insulation varies with age, moisture content, and the applied voltage. A megohmmeter is similar to a typical ohmmeter except it uses a hand-cranked permanent-magnet dc generator as a voltage source rather than a battery. The dc generator is cranked by the operator while making an in-

Fig. 16-10. A ground-fault indicator.

Courtesy Leviton Manufacturing Co., Inc.

Courtesy James G. Biddle Co.

Fig. 16-11. A megohmmeter.

...sulation test. Fig. 16-12 shows a diagram of a megohmmeter circuit. This circuit is essentially the same as any series ohmmeter with the exception that a dc generator is used as the voltage source.

Periodic insulation tests should be made on all large power equipment. As insulation breaks down with age, the equipment starts to malfunction. A good method is to develop a periodic schedule for checking and recording insulation resistance. Then, it can be predicted when a piece of equipment needs to be replaced or repaired. A resistance-versus-time graph can be made and the trend shown on the graph can be noted. A downward trend (a decrease in insulation resistance) over a specific time period indicates that an insulation problem exists.

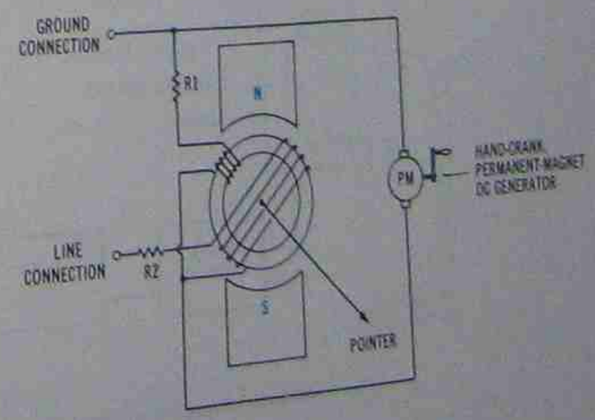


Fig. 16-12. Circuit diagram of a megohmmeter.

CLAMP-TYPE METERS

Clamp-type meters, such as the one shown in Fig. 16-13, are popular for measuring current in power lines. This indicator may be used for periodic checks of the current by clamping it around a power line. It

is an easy-to-use and convenient maintenance and testing instrument.

The simplified circuit of a clamp-type current meter is shown in Fig. 16-14. Current flow through a conductor creates a magnetic field around the conductor. The varying magnetic field induces a current into the iron core of the clamp portion of the meter. The meter

Courtesy RCA Corp.

Fig. 16-13. A clamp-type current meter.

scale is calibrated so that when a specific value of current flows in a power line, it will be indicated on the scale. Of course, the current flow in the power line is proportional to the current induced into the iron core of the clamp-type meter. Ordinarily, the clamp-type meter also has a voltage and resistance function which utilizes external test leads. Thus, the meter can be used to measure other quantities.

TELEMETERING SYSTEMS

When a quantity being measured is indicated at a location some distance from its transducer or sensing element, the measurement process is referred to as *telemetering*. Many types of metering systems fit this definition. However, telemetering systems are usually used for long-distance measurement or for centralized measurement systems. For instance, many industries group their indicating systems together to facilitate process control. Another example of telemetering is the centralized monitoring (on a regional basis) of electrical

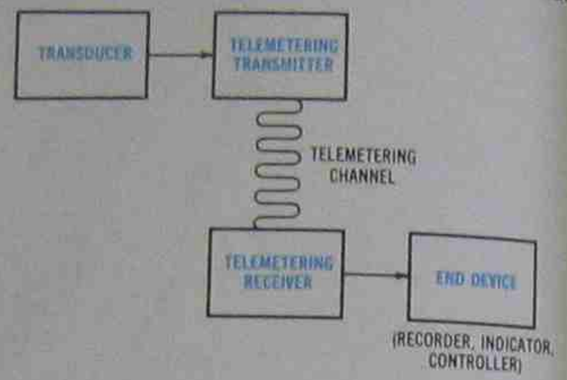


Fig. 16-15. Block diagram of a basic telemetering system.

power by utility companies. These systems are similar to other measuring systems except that a transmitter/receiver communication system is usually involved.

Types of Telemetering Systems

Many types of electrical and physical quantities can be monitored by using telemetering systems. The most common transmission media for telemetering systems are: (1) wire—such as telephone or telegraph lines, (2) superimposed signals—which are 30- to 200-kHz signals carried on electrical power distribution lines, and (3) radio-frequency signals—from am, fm, and

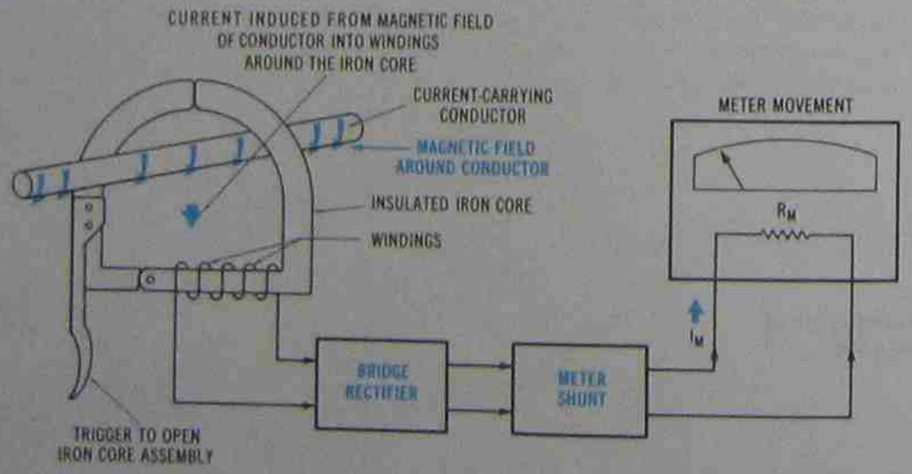


Fig. 16-14. Circuit diagram of a clamp-type current meter.

...-modulation transmitters. The block diagram of ... type of telemetering system is shown in Fig. 16-15. ... this type of system, a dc voltage from the transducer ... used to modulate an am or fm transmitter. The radio-... frequency (rf) signal is then received at another loca-... and converted back into a dc voltage to activate ... end device. The end device, which may be lo-... a considerable distance from the transducer, ... be a chart recorder, a hand-deflection meter, or ... a process controller. Digital telemetering is ... since binary signals are well suited for data ... In this system, the transducer output is ... to a binary code for transmission.

Summary for Telemetering Systems

Again, telemetering is the measurement of some quantity at an area that is distant from its origin. For instance, it is possible, by using telemetering systems, to monitor on one meter the power used at several different locations. Almost any quantity value, either electrical or nonelectrical, can be transmitted by using some type of telemetering system. A basic telemetering system has: (1) a transmitting unit, (2) a receiving unit, and (3) an interconnection method. Electrical power systems frequently utilize telemetering systems for the monitoring of power.

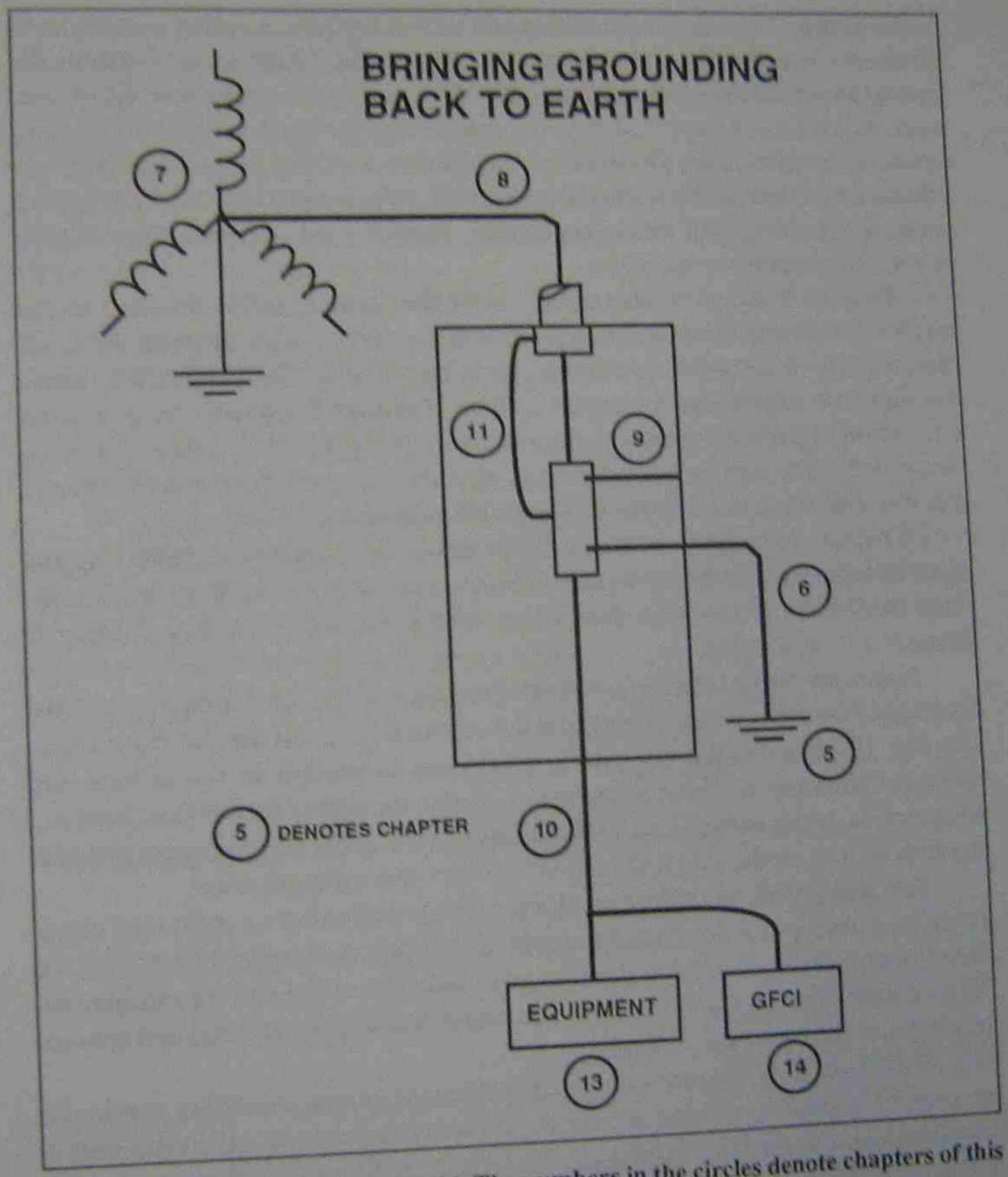


Fig. I–1 Diagram of chapters 5–14. The numbers in the circles denote chapters of this book.

Grounding Electrode System

3 5555 07073772 3

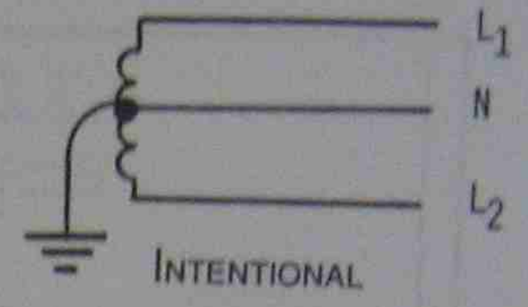
ELECTRICAL GROUNDING

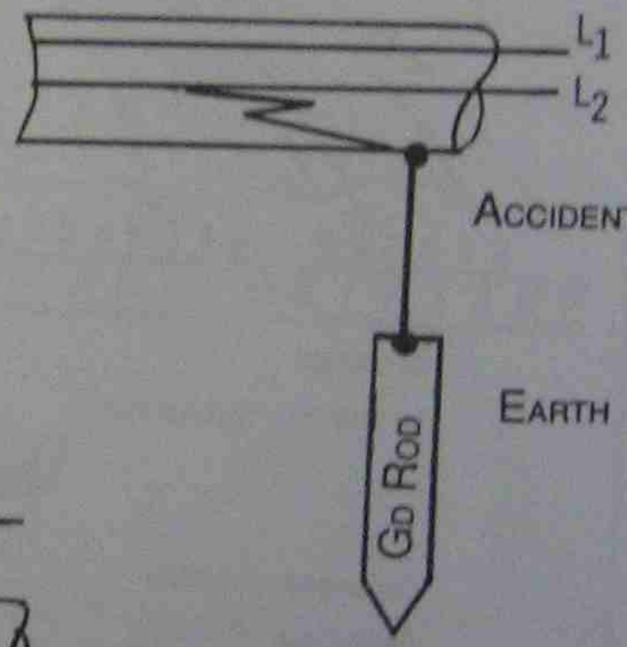
Based on the 1987 National Electrical Code®

Ronald P. O'Riley

GROUND

A CONDUCTING CONNECTION, WHETHER INTENTIONAL OR ACCIDENTAL, BETWEEN AN ELECTRICAL CIRCUIT OR EQUIPMENT AND THE EARTH, OR TO SOME CONDUCTING BODY THAT SERVES IN PLACE OF THE EARTH*





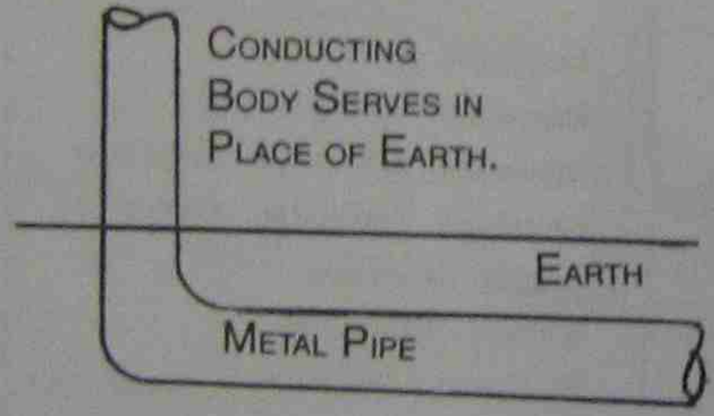


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Fig. 1–4 Definition of *ground*.

been made. The phrase "to earth, or to some

The grounding is continuously there, waiting to conduct fault current, should the occasion arise. Part of grounding's job is maintaining all non-

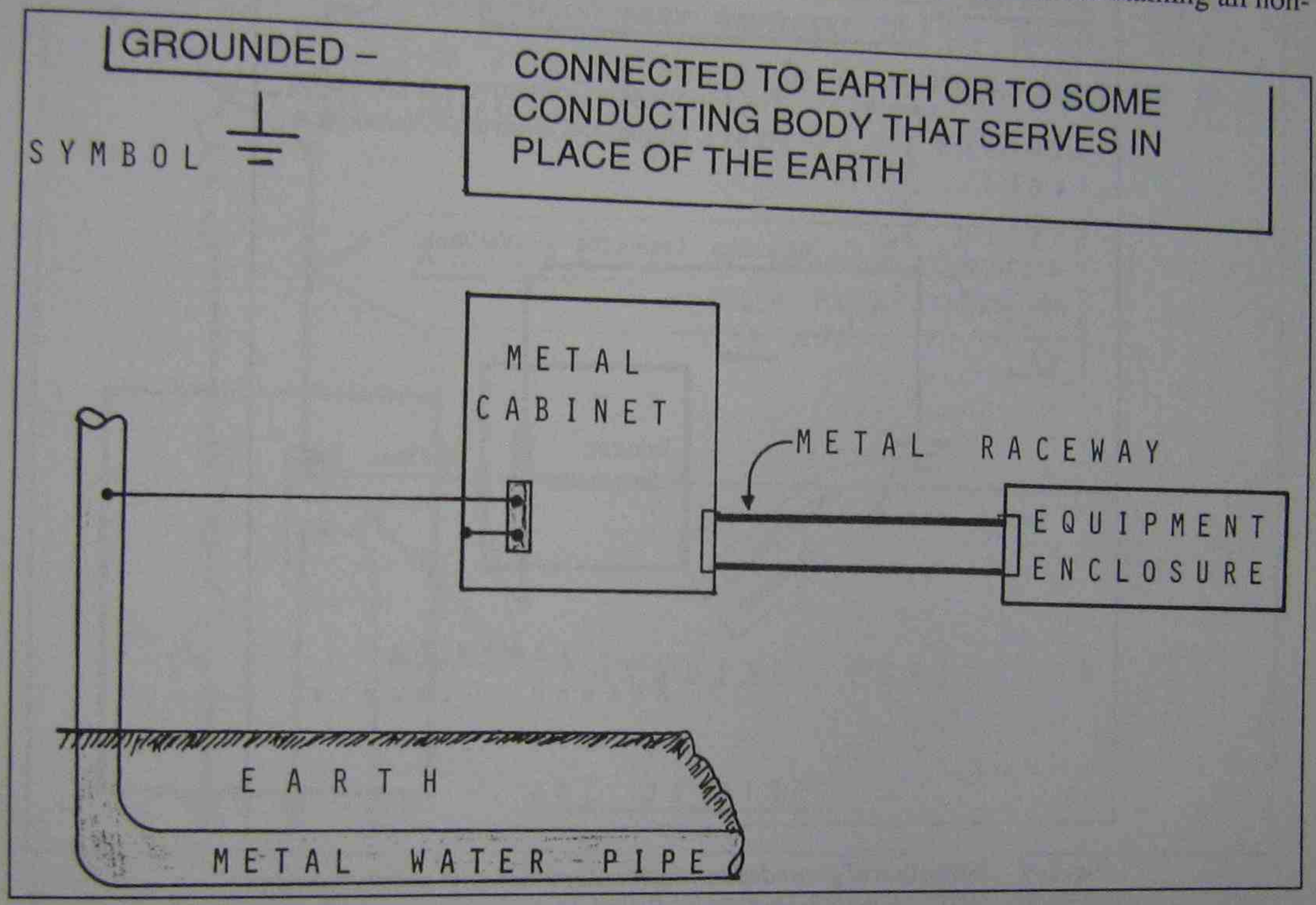


Fig. 1–5 Definition of *grounded*. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright ©, 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

continuously there for all to enjoy.

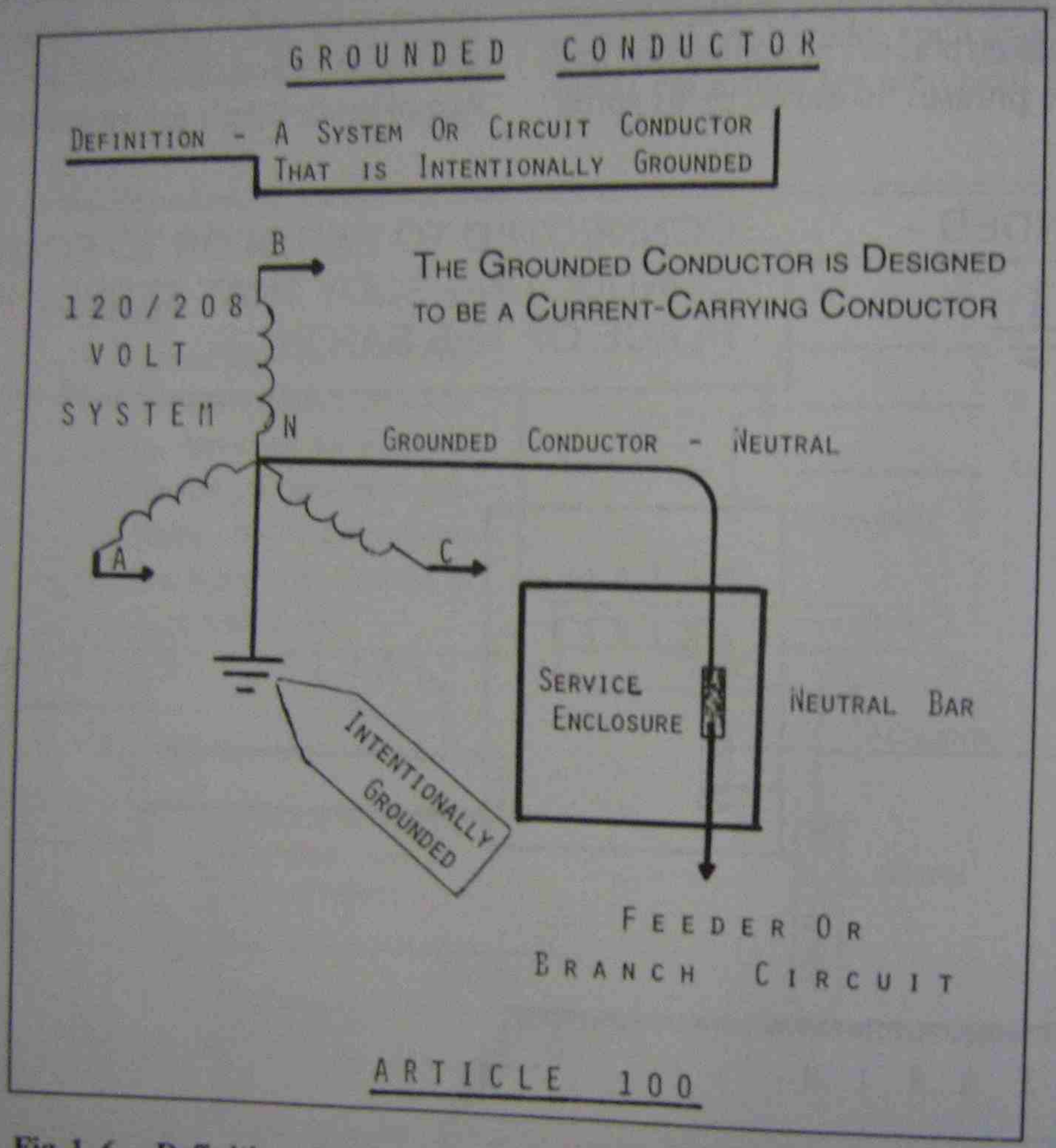


Fig. 1–6 Definition of *grounded conductor*. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright ©, 1986, National Fire Protection Association, Quincy, MA 02269.

Each of the three grounding conductors will be taken up individually later in this text.

to emphasize the particular point under discussion.

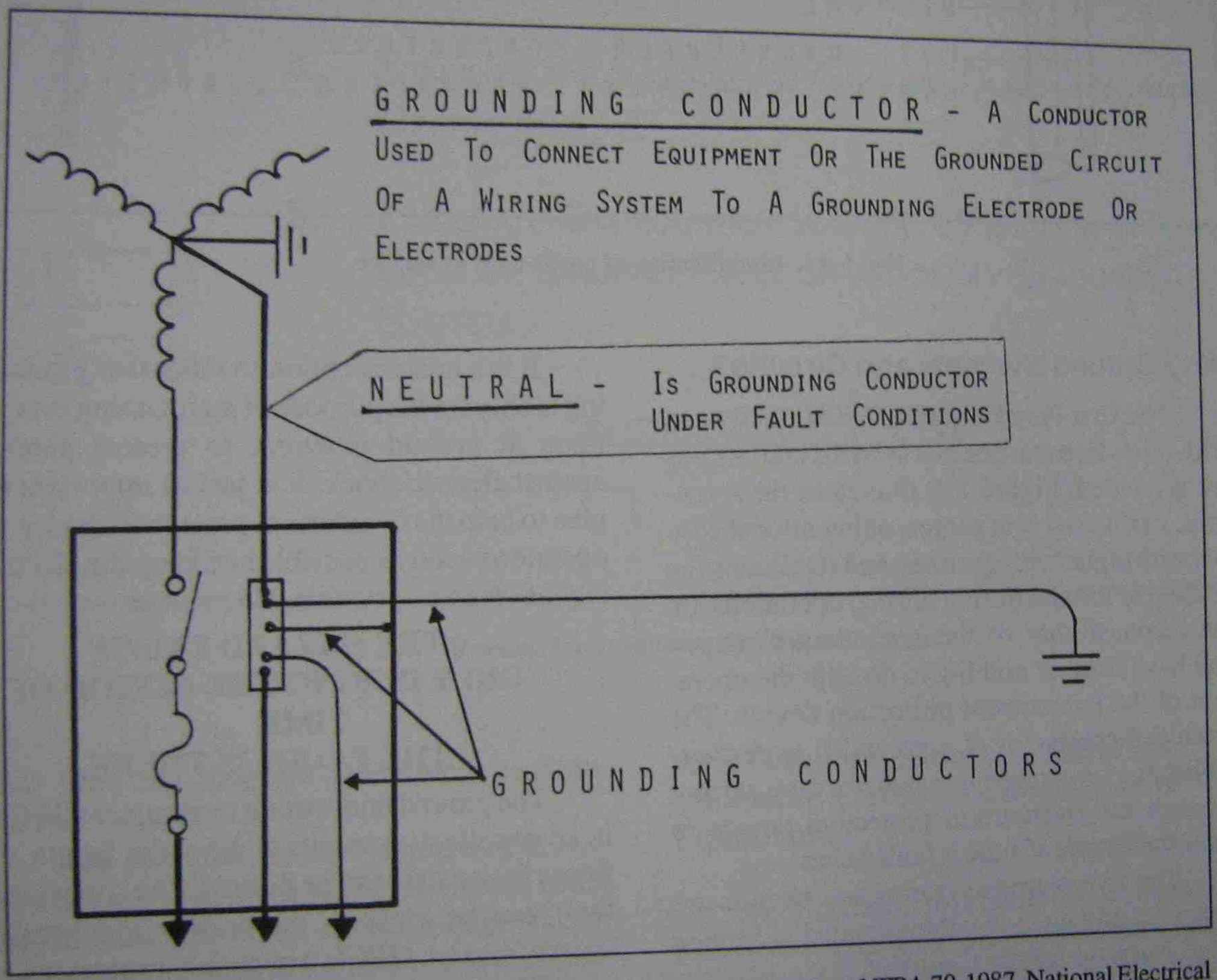


Fig. 1–7 Definition of *grounding conductor*. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright ©, 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the

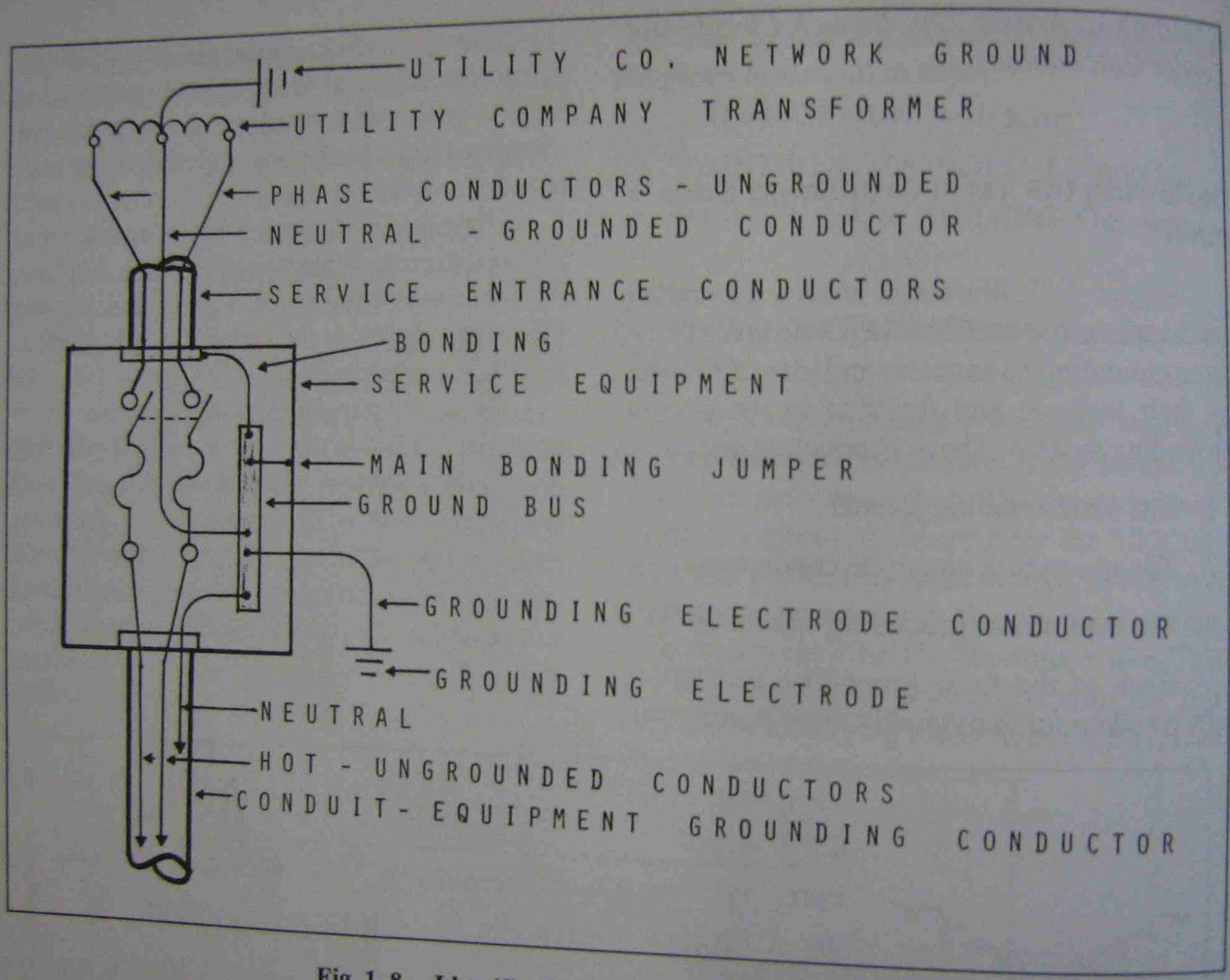


Fig. 1–8 Identification of terms used at service.

ELECTRODE

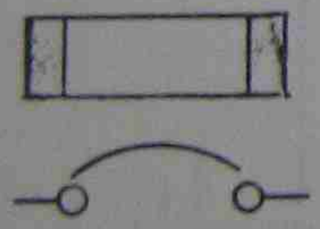
WHY GROUND SYSTEMS AND CIRCUITS?

TO LIMIT VOLTAGE DUE TO

1. Lightning
2. Line Surges
3. Unintentional Contact with Higher Voltage Lines

AND TO

4. Stabilize the Voltage to Ground During Normal Operations
5. Facilitate Overcurrent Device Operation in Case of Ground Fault on a Solidly Grounded System



SECTION 250-1 (FPN)

Fig. 1-9 Reasons for grounding systems and circuits.

Number one is to "limit the voltage to ound." Number two is to "facilitate overcur- nt device operation." Once again, the concern to limit the voltage and limit the current.

The third reason, although not specifically ted in this FPN, is to drain leakage and/or tic electrical currents to ground. An example grounding the shield of a shielded cable. ecial recognition is given in *Article 517, alth Care Facilities* to static and leakage rents. Draining leakage and static currents to und helps reduce electrical noise.

What Is Effective Grounding?

Figure 1–11 illustrates what must be taken into consideration to have effective grounding. A more detailed look is possible when it is broken down into parts.

The path to ground covers the installation of three things. These are:

1. Circuits
2. Equipment
3. Conductor enclosure

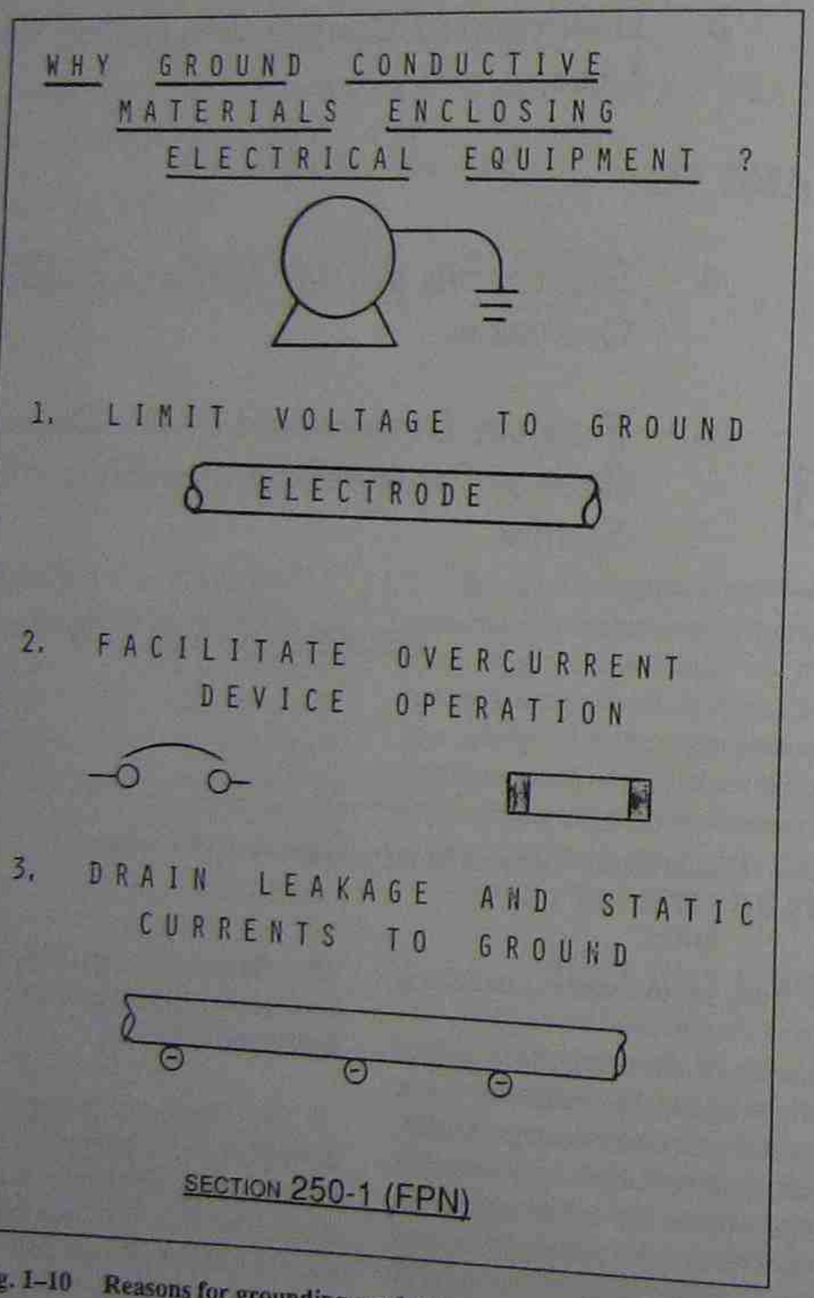


Fig. 1–10 Reasons for grounding conductive materials and enclosures.

The path to ground must:

1. Be permanent
2. Be continuous
3. Have ampacity to conduct any fault current *safely*
4. Have low impedance

The impedance must be kept low for two reasons. These are:

1. To limit the voltage to ground
2. To facilitate the operation of the circuit protective devices

Comment: Note how effective grounding is required in three different installations—cir- cuits, equipment, and conductor enclosures.

The *path to ground* is something that is built into the electrical circuit at the time it is installed. All connections are made permanen and continuous. The conductor that is installe is large enough to carry potential fault curren

Impedance is the opposition to the flow o current. Everything that can be done must b

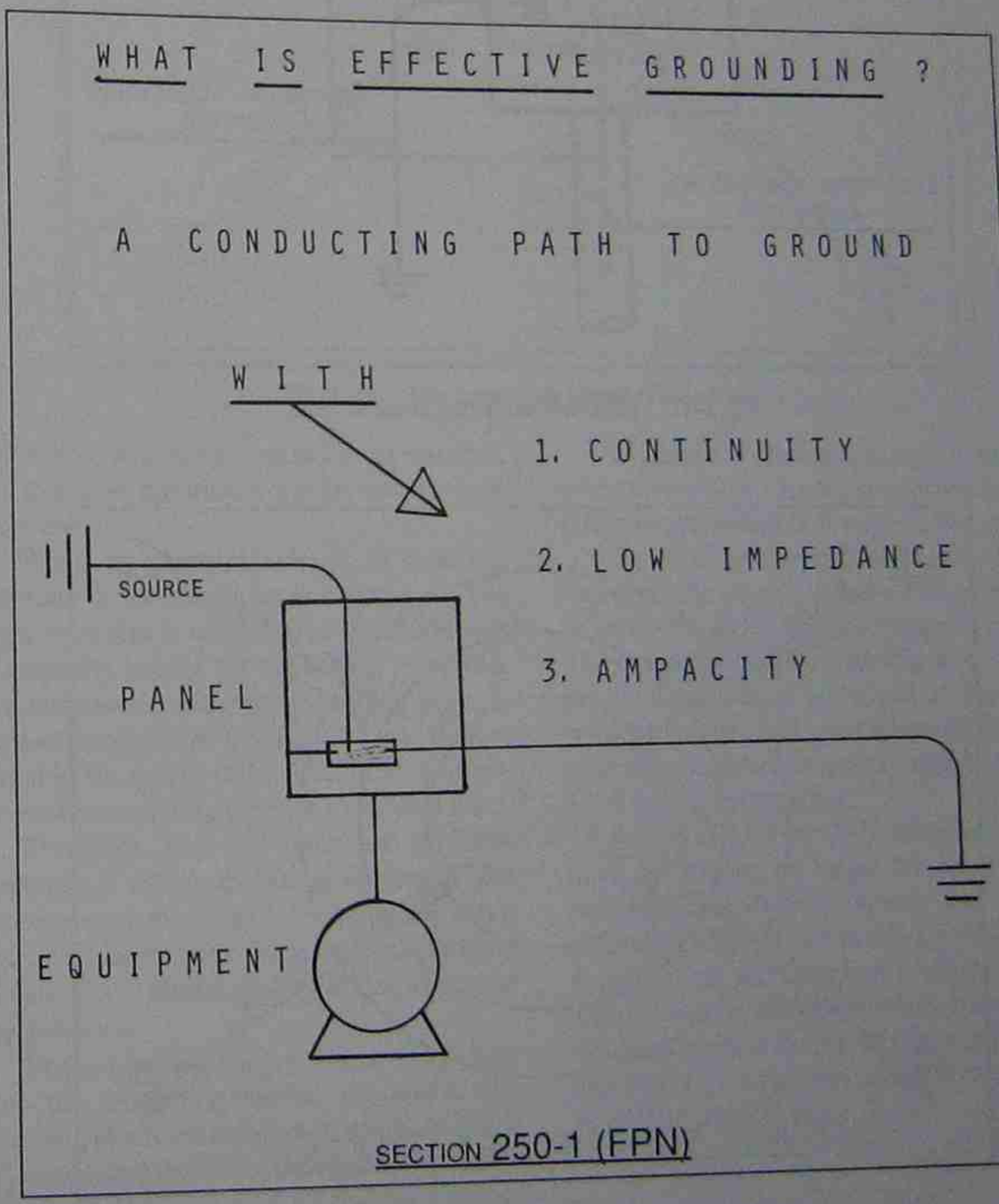


Fig. 1–11 Requirements for effective grounding.

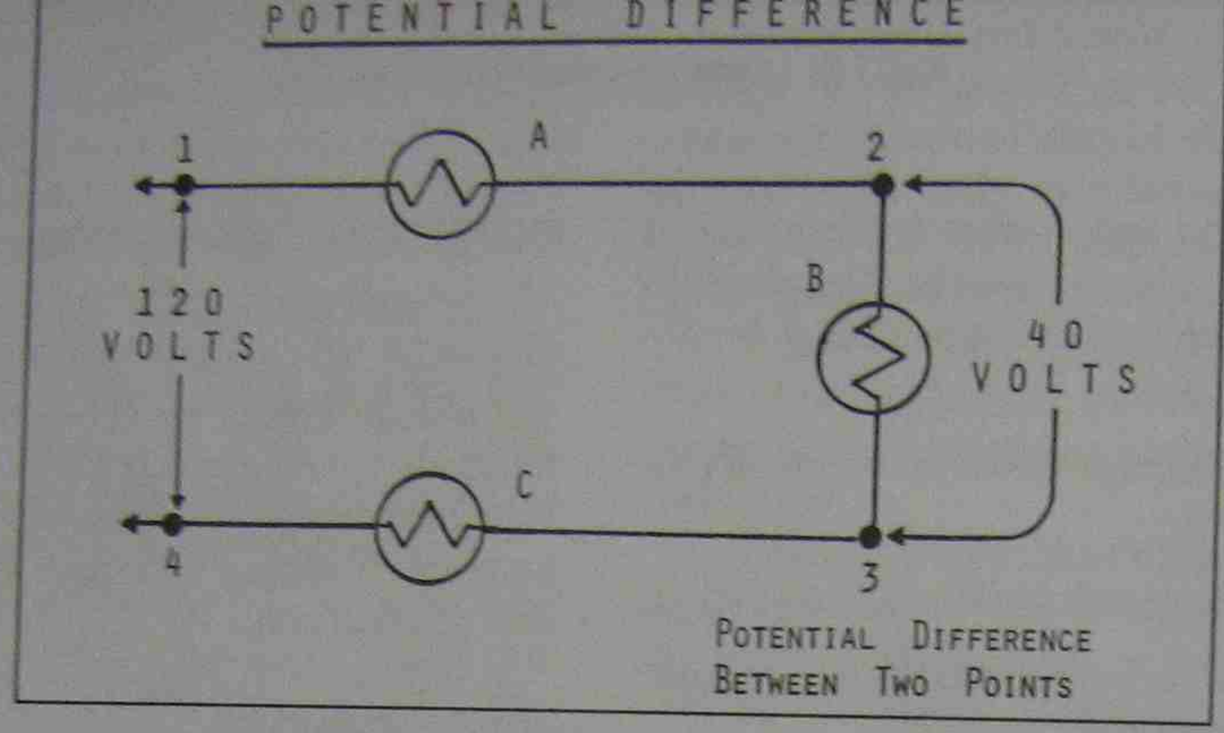


Fig. 2–7 Potential difference between two points.

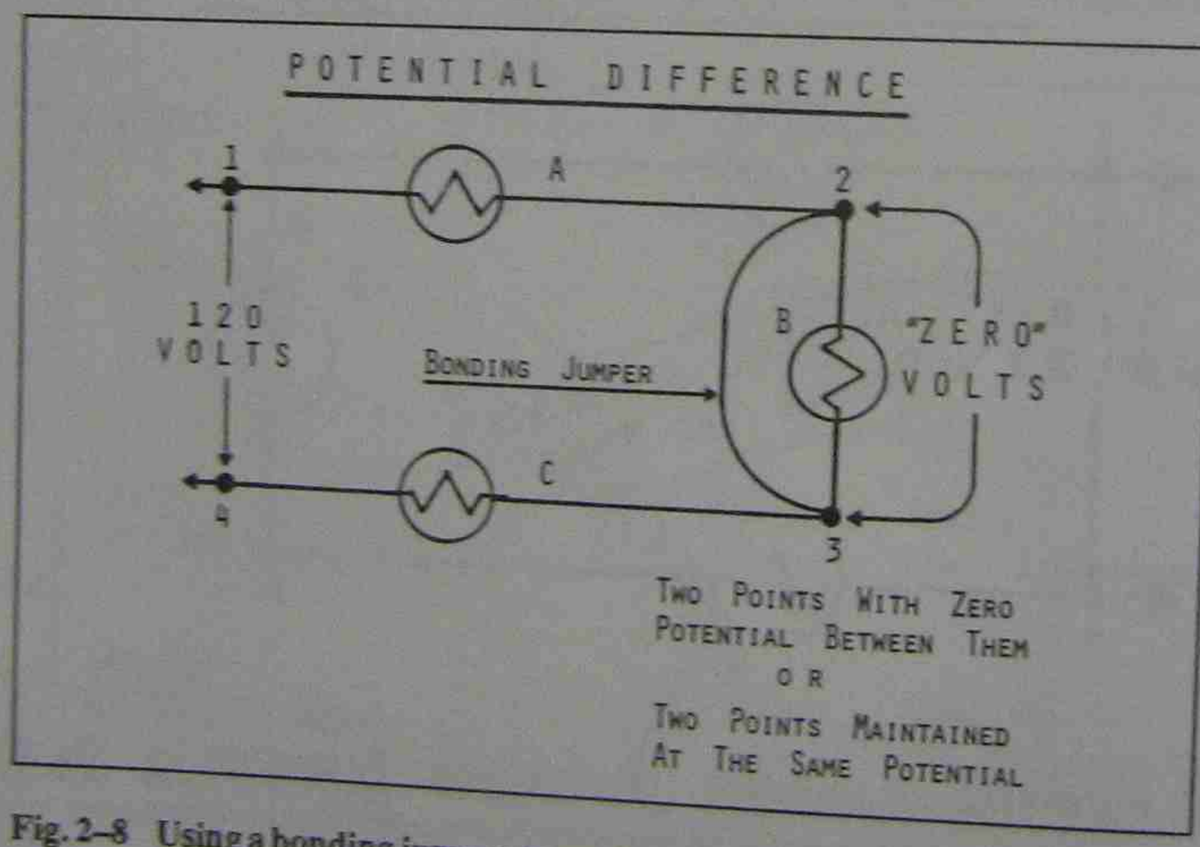


Fig. 2–8 Using a bonding jumper to maintain two points at the same potential (zero).

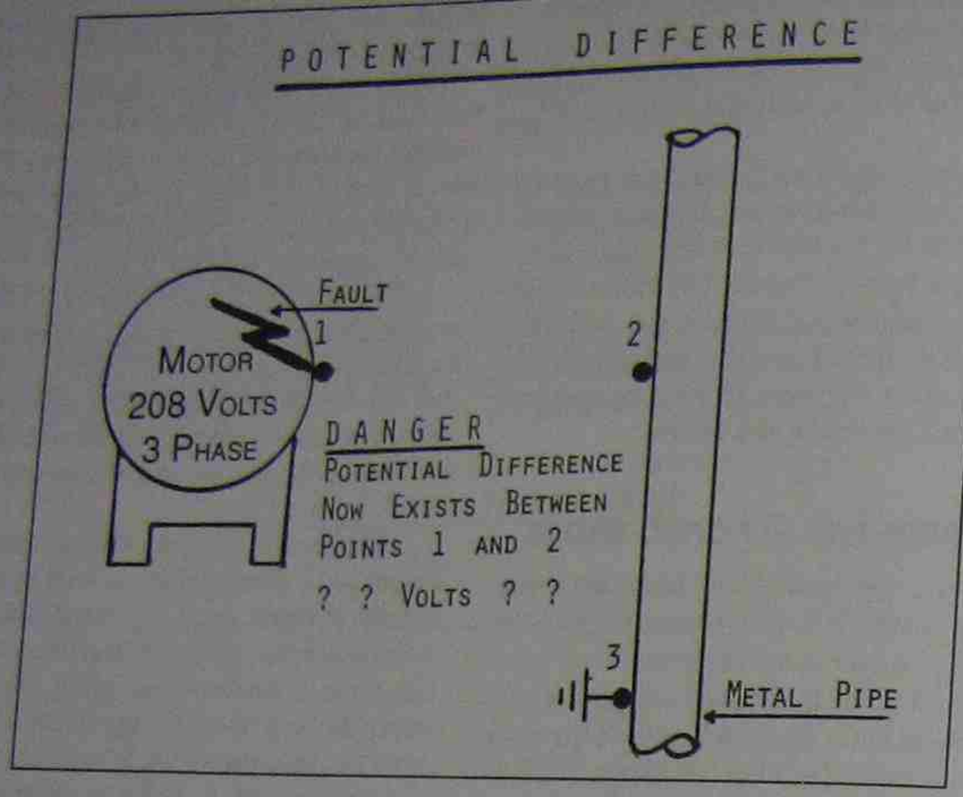


Fig. 2–10 Motor ground fault. A hazard now exists.

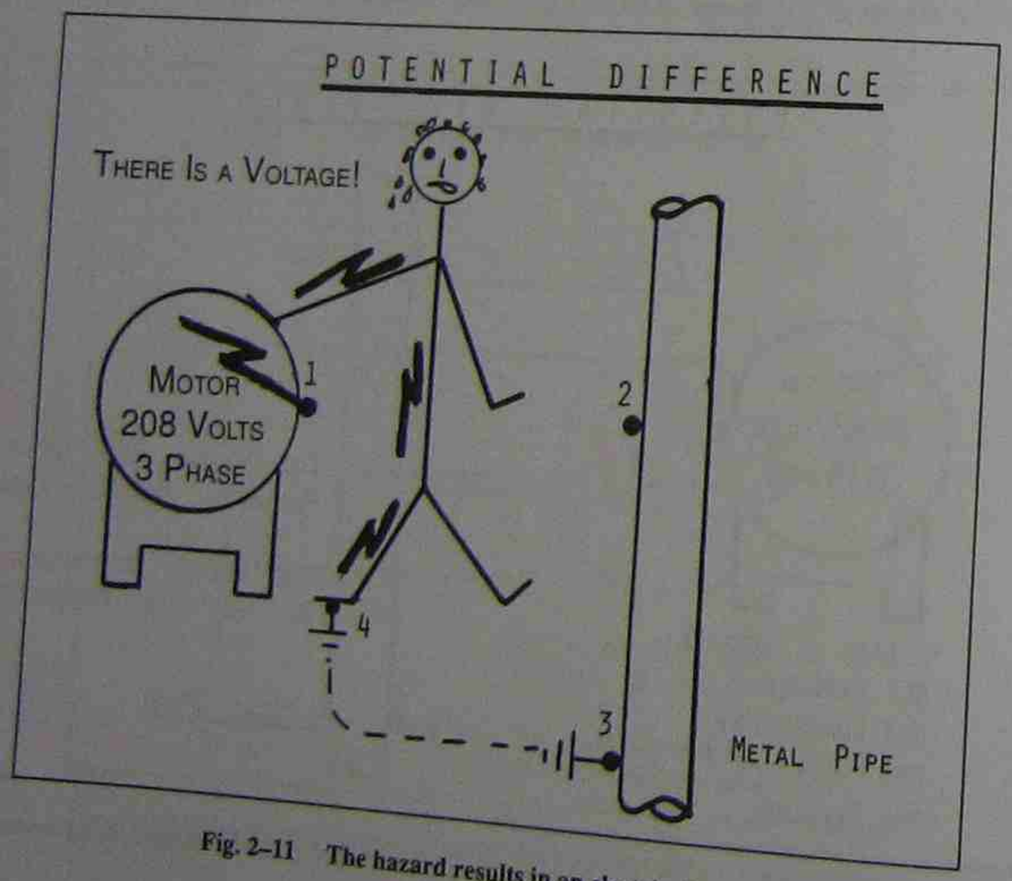


Fig. 2–11 The hazard results in an electric shock.

and the grounded water pipe. This actually creates a complete electrical circuit through the individual, who now receives an electric shock. Note the path of the current through the body.

What will the voltage across the victim be? That all depends on how good a contact the victim has made to complete the circuit and what the impedance of the arc and the contact within the motor are.

In figure 2–13, an equipment bonding jumper has been installed. Such an installation would be part of a properly grounded system and would eliminate the hazards that existed. However, the bonding jumper would not be run open from the water piping to the motor frame. The equipment grounding conductor would be installed with the regular circuit conductors. By adding the bonding jumper, the potentia

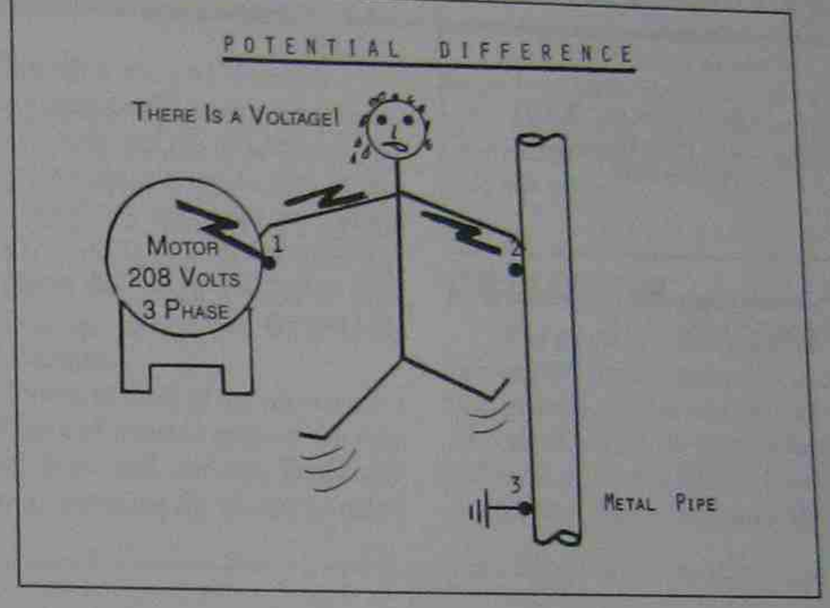


Fig. 2–12 Another shock hazard exists.

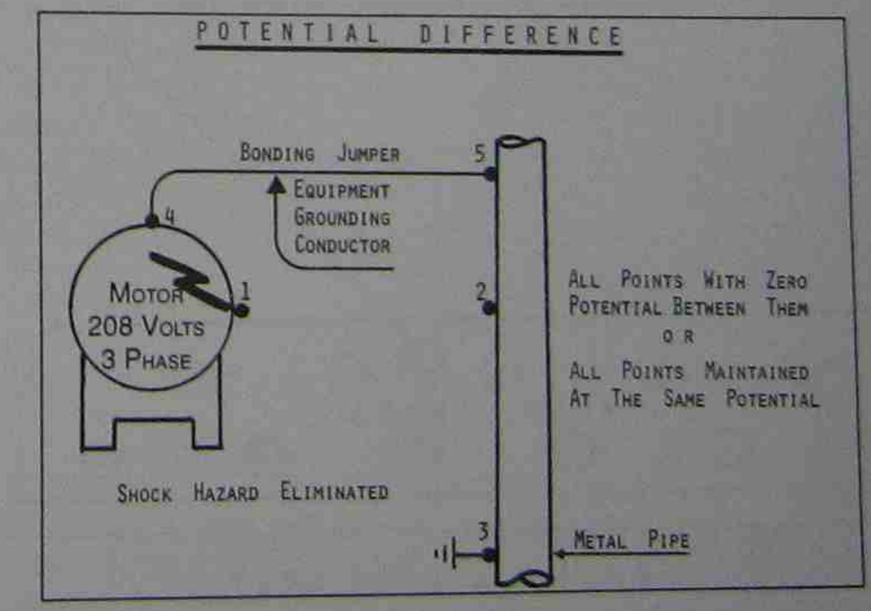
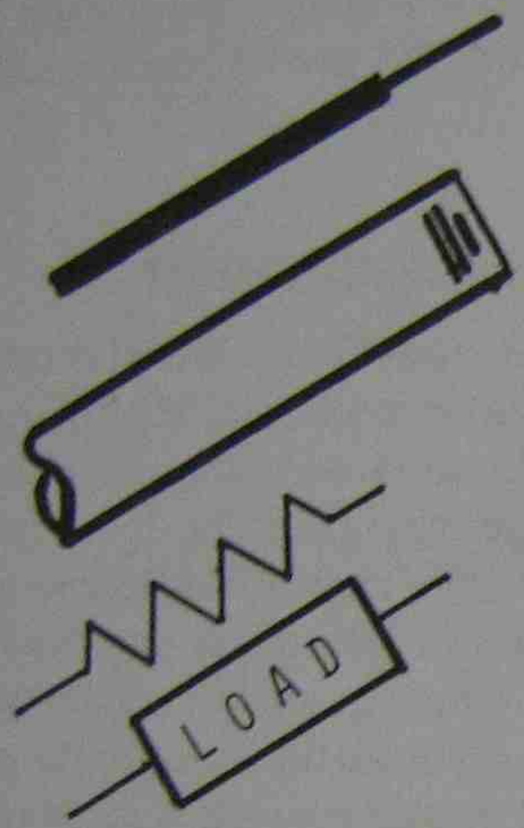


Fig. 2–13 Shock hazard eliminated by installing a bonding jumper.

RESISTANCE ----- "R"



CAUSED BY THE MATERIALS OF
WHICH THE CIRCUIT IS BUILT

CONDUIT
WIRE
LOOSE CONNECTIONS
TERMINATIONS
PANELS
EARTH
WET – DRY – SOGGY

MEASURED IN OHMS

IS IN GROUNDING CIRCUIT

Fig. 3–8 Pure resistance.

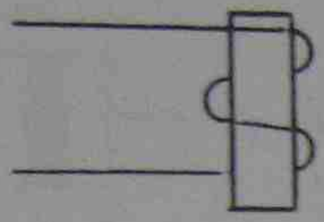
conductors have resistance in them. Conduit offers resistance to the flow of current. When improperly or poorly made, terminations, connections, and splices can introduce resistance

circuit (figure 3–9). The inductance is caused by the alternating current's magnetic field.

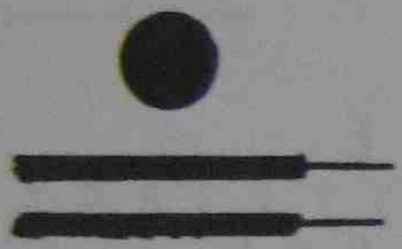
When current flows through a conductor, it

ALTERNATING-CURRENT CIRCUITS

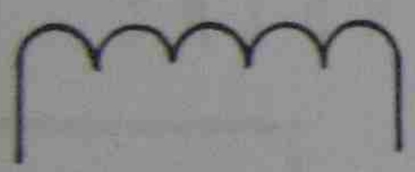
INDUCTIVE REACTANCE ----"X_L"



A CURRENT EFFECT CAUSED BY INDUCTANCE



MUTUAL INDUCTION AND SELF-INDUCTION IN CONDUCTORS



CURRENT'S MAGNETIC FIELD

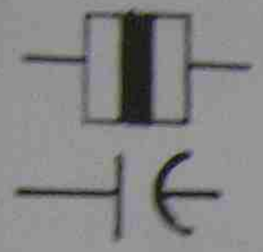
MEASURED IN OHMS

IS IN GROUNDING CIRCUIT

Fig. 3–9 Inductive reactance.

ALTERNATING-CURRENT CIRCUITS

CAPACITOR ---



CONSISTS OF TWO CONDUCTORS SEPARATED BY AN INSULATOR

CAPACITIVE REACTANCE---- "X_C"

A VOLTAGE EFFECT

OPPOSITION DUE TO CAPACITANCE IN CIRCUIT

MEASURED IN OHMS

IS IN GROUNDING CIRCUIT

Fig. 3–11 Capacitive reactance.

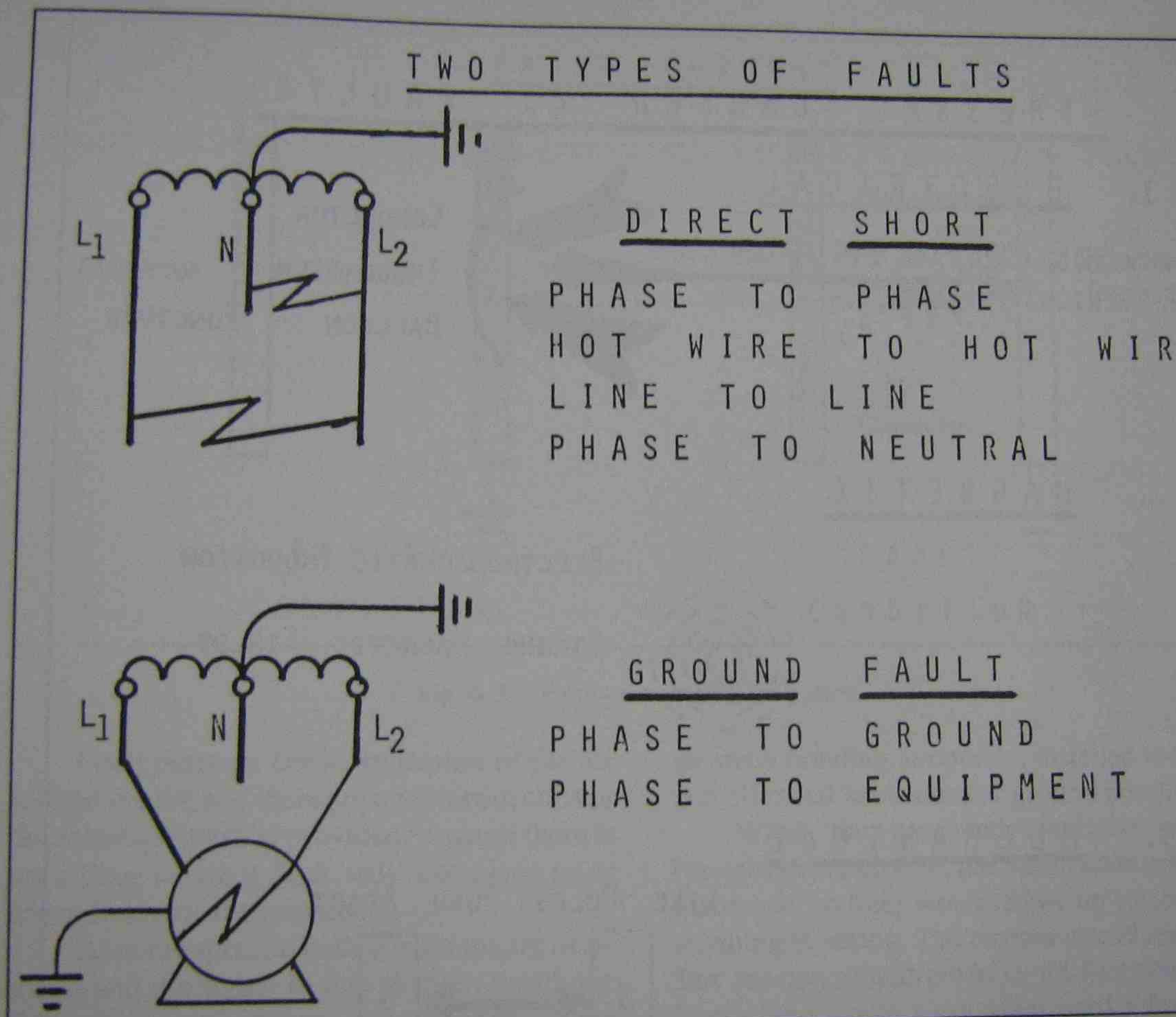
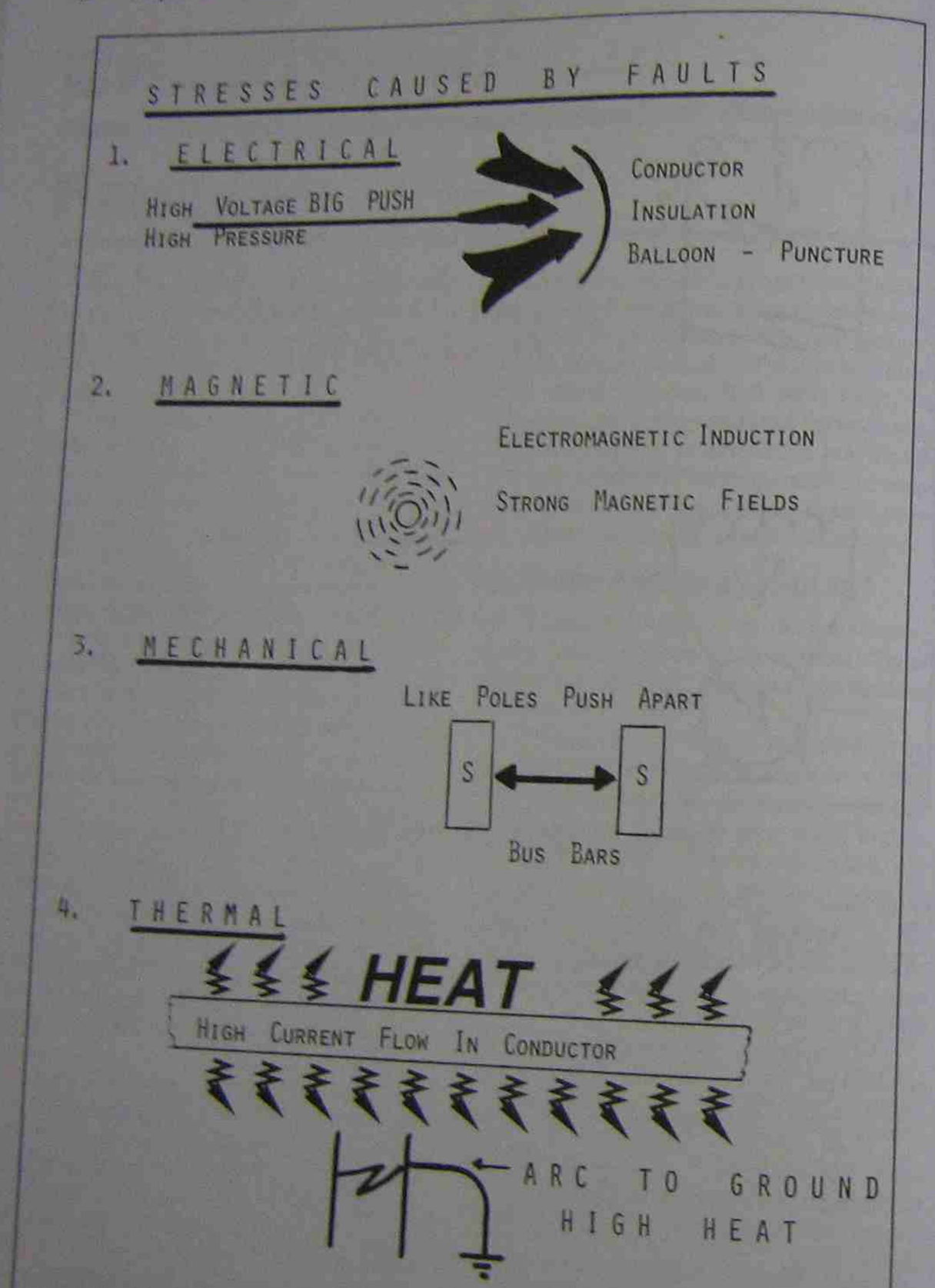


Fig. 4–1 Two types of faults: direct short and ground fault.



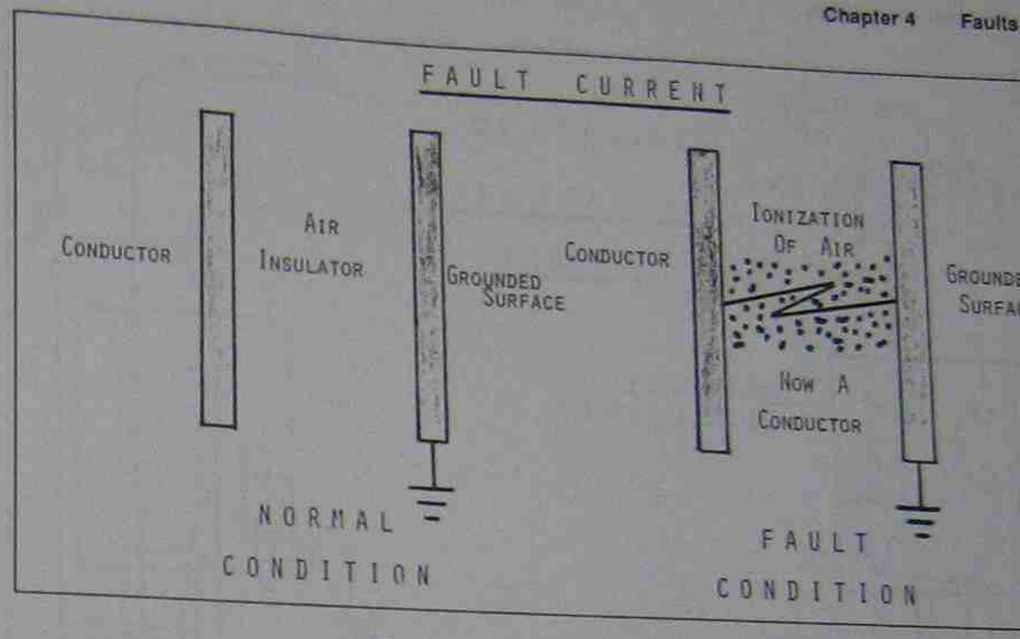


Fig. 4–3 Fault-current and ionization.

Fault currents cause ionization of the air around the arc and there are no blowout coils or deionization method provided, because there is no telling where a fault will take place in or around electrical equipment.

As some specific fault conditions are illustrated and discussed in this chapter, watch the flow of current in the regular circuit and in the alternate path, the grounding circuit. Most of the figures use two types of diagrams. The wiring diagram shows the point-to-point connections of the circuit and the one-line or schematic diagram shows the scheme of operation. What is happening in each figure can often be seen quicker, and the current flow followed easier, on the one-line diagram. In setting up some of these fault situations, Code regulations are not taken into consideration. However, some of the faults will graphically illustrate why a certain Code regulation exists.

GROUNDED SYSTEM FAULTS

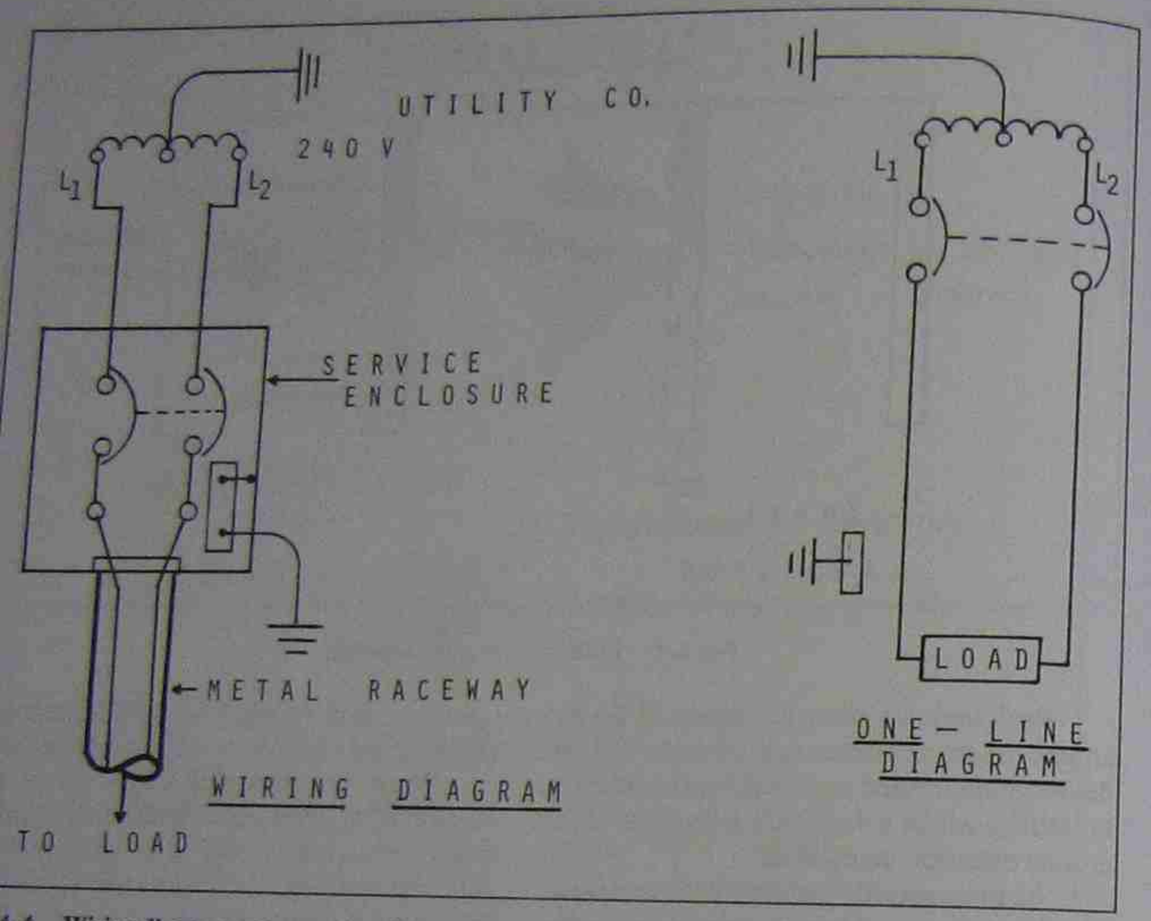
Figure 4–4 illustrates a 240-volt, single-phase service. The utility company has the center tap of the transformer grounded. There is no grounded conductor brought to the service because there is no need for one. The service

the main bonding jumper are installed tain all metal enclosures at ground pot

When the grounded conductor brought to the service, the installation made and nothing would show up to anything is wrong. The motors would The service would perform its funct Everything would work great until a curred.

Figure 4–5 illustrates a direct sho to-line fault. The total fault current ha through the circuit breaker, which circuit breaker a chance for quick tr the case of the direct short, the curren one path to travel, and that includes through the overcurrent protectio There is a low-impedance path for the flow. The low opposition to the flow will allow a small circuit breaker, su or 20-amp breaker, to trip, elimi hazard with little or no damage done. the circuit rating, the greater the cu interrupted, and the greater the po damage before the overcurrent pro vice can operate.

The fault exists only until the protective device operates. The afte



4–4 Wiring diagram and a one-line diagram of a two-wire service without grounded conductor brought rvice—no-fault situation.

Figure 4–6 illustrates what happens when is a phase-to-ground fault. The situation is iderably different here, although the illus- n might indicate that there is a fault in the uit, close to the service. This is for illustra- urposes only. In reality, the fault could be ece of equipment or any place on the load f the service equipment.

n this situation, the low-impedance path overcurrent protection device is not there. this type of fault happens, there are a r of oppositions (impedances) to the flow that must be taken into considera- hose illustrated in Figure 4–6 are:

Impedance of the earth or ground
Impedance of raceway and enclosure path
Impedance of grounding electrode path

Z_4 = Impedance of utility grounding electrode path

Note on the figure how all the impedances are connected in series. The total Z is the total opposition to the flow of current. The higher the Z, the lower the current, the less chance the overcurrent protection device has to clear the fault, and the longer the hazard exists. This fault could exist for a period of time and until enough damage is done to result in a possible phase-to-phase fault.

In this case, the fault current has to travel from the point of the fault, through the metal raceway, then through the metal enclosure of the service to the main bonding jumper, and then to the ground bar. From there it flows on the grounding electrode conductor to the grounding electrode and into the earth, then through the ground to the grounding electrode of the utility company, through the grounding electrode conductor of the utility company, through the transformer to L_2, through the overcurrent protection device, and back to the fault.

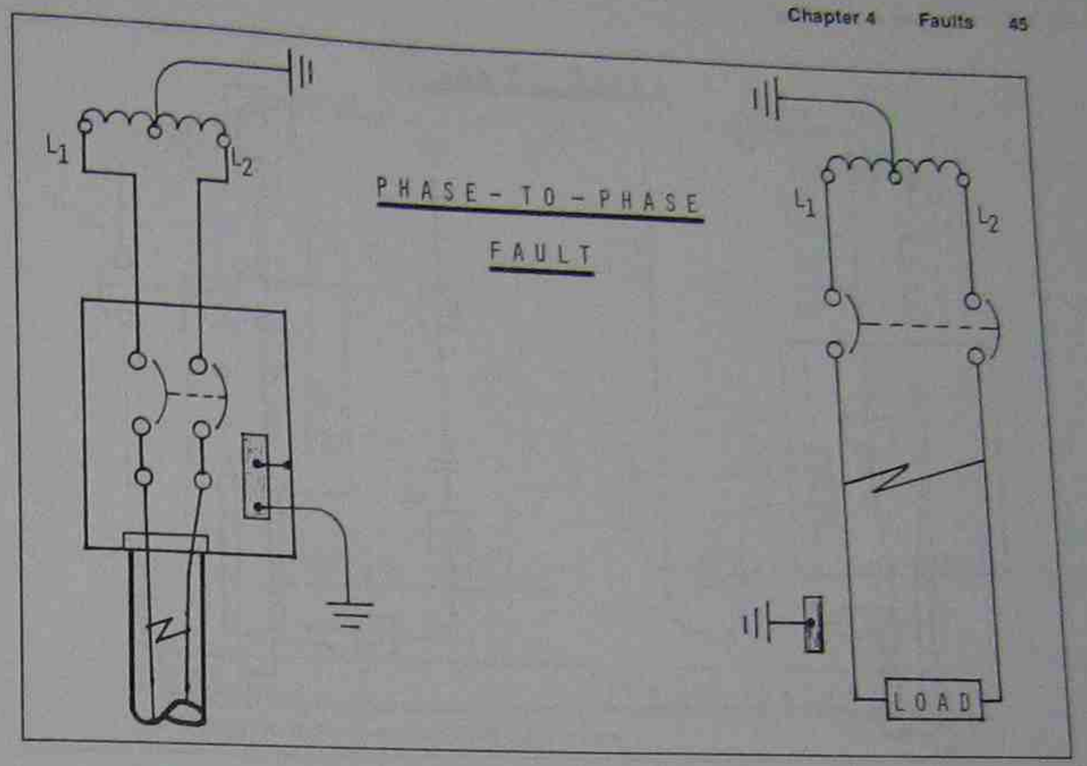


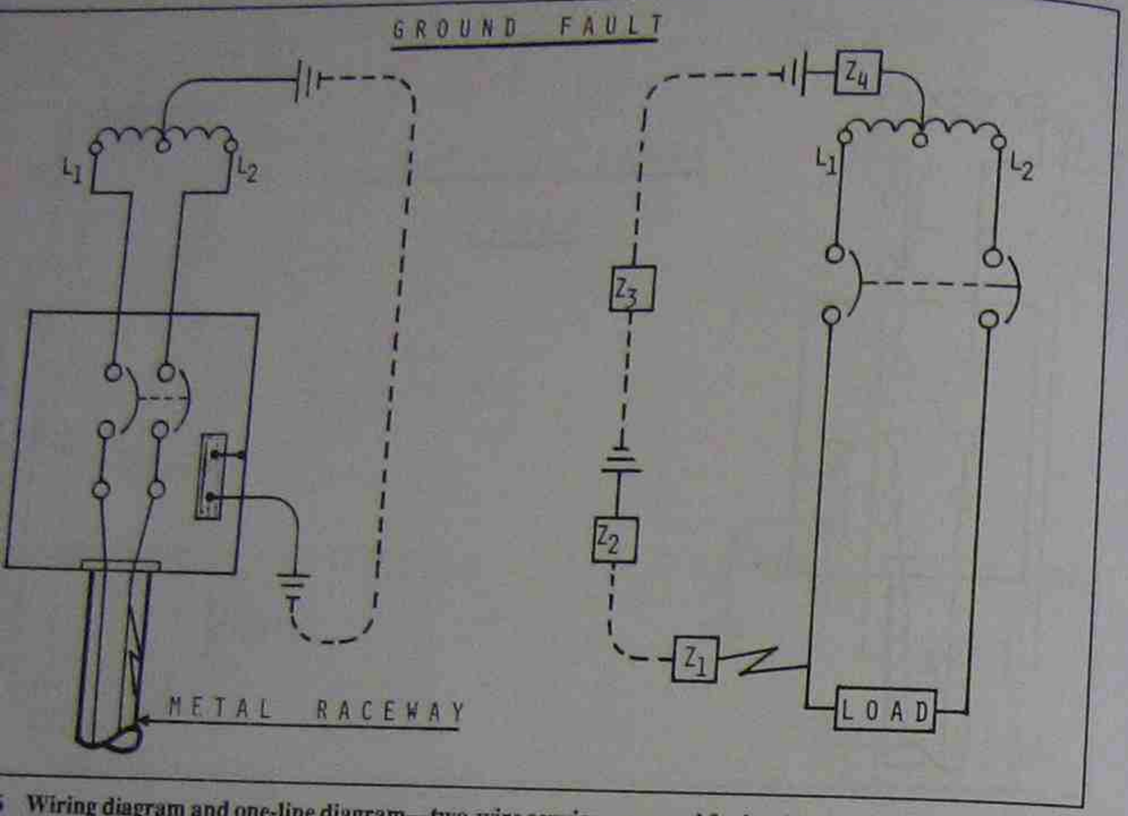
Fig. 4–5 Wiring diagram and one-line diagram of two-wire service without grounded conductor brought to service—direct short—line-to-line fault.

Figure 4–7 brings the grounded conductor from the utility transformer to the service equipment, even though it is not needed. This is done according to the Code. Once again everything will work very nicely, until trouble pops up and a fault takes place. Should a line-to-line fault occur, it would be the same as the one previously illustrated in Figure 4–5.

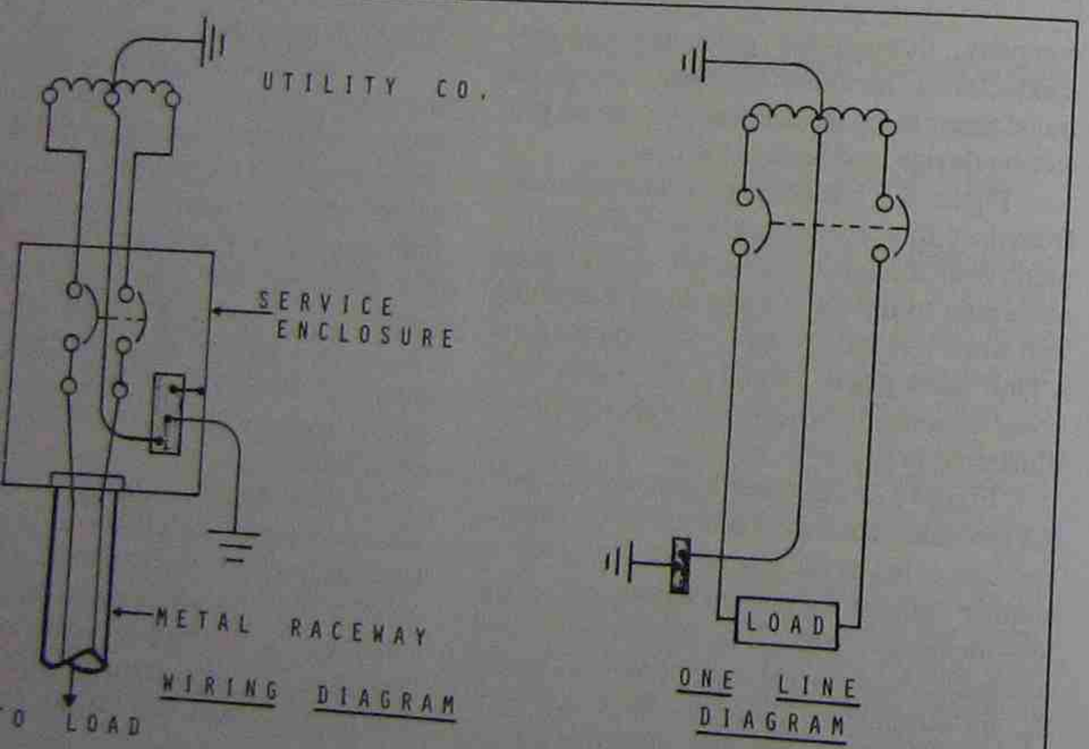
Figure 4–8 illustrates a ground fault, with the grounded conductor brought to the service and connected to the ground bus. Now there is another path for the current to flow on, a very low-impedance path. It is easy to see in the schematic diagram that two impedances, Z_3 and Z_4, are eliminated. These are the two largest impedances in the previous grounding circuit (Figure 4–6). At first it might seem like the impedance is cut in half, but actually it is cut by close to 90 percent.

The question often asked is, Will there be any current flow through the grounding electrodes and the earth when the grounded conductor is brought to the service? This is best answered with a question: Is the ground path through the earth a parallel path? The answer is yes. There is current flow in all branches of a parallel circuit; therefore, there will be some current flow through the earth. However, the amount of current that will take the earth ground path is very small because of the very high impedance.

A very interesting thing takes place here when this ground fault happens. Note how the fault current used the grounded conductor to travel back to the transformer. During the fault condition, the "grounded conductor" also became the "equipment grounding conductor." Things can change very fast in the grounding circuit.



5 Wiring diagram and one-line diagram—two-wire service—ground fault without grounded conductor t to service.



Wiring diagram and one-line diagram—two-wire service—with grounded conductor brought to no-fault situation.

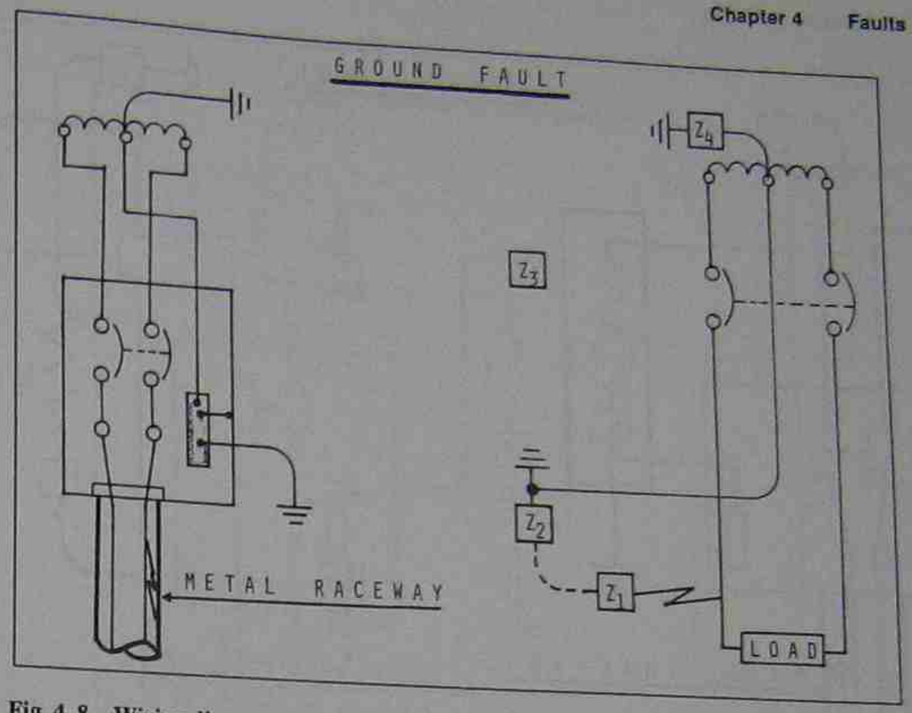


Fig. 4–8 Wiring diagram and one-line diagram—two-wire service with grounded conductor brought to service—ground-fault current flow.

IMPEDANCE GROUNDED SYSTEMS

Until now the intention has been to build a circuit that will allow the overcurrent protective device to act automatically by reducing the impedance of the ground fault path to a minimum, thereby limiting the time the fault exists. Now we find that there are situations where the automatic tripping of the device could be more of a disadvantage than an advantage. For example, if a factory is operating on a process control system, and the overcurrent device causes the lines to shut down without notice, the operators could be put in a very dangerous situation and/or a considerable amount of damage could occur to equipment and materials.

Impedance grounding is used to solve this problem of automatic tripping. However, the intent is still to get the fault cleared as soon as possible under controlled conditions. Note in Figure 4–9 how the grounding resistor and its equipment are mounted in an enclosure separate from the service equipment. It could also be mounted within the service enclosure itself.

Impedance grounding is used to limit the fault current and to monitor any ground currents that might flow. Figure 4–9 illustrates an impedance-grounded system. The illustration uses a resistor, but an impedance coil is also used. The "M" indicates the monitoring equipment used in conjunction with the impedance. It could be an ammeter or a relay that would operate the circuit disconnecting means and give an audio or visual alarm, or a combination of both.

The grounding impedance acts just like any other current-limiting resistor used to limit current flow in a series circuit. The impedance used is a calculated amount of opposition to the flow of current. This is usually limited to a very low current, sometimes in the milliamp range. Using a current-limiting resistor limits the fault current. Although an arc is used on the illustration to indicate a fault, there may never be an arc with impedance grounding. The fault may just be an accidental connection to ground that can be corrected before serious damage happens.

Current-limiting resistors are used for starting direct-current or alternating-current motors, for signal or indicating lights, and for

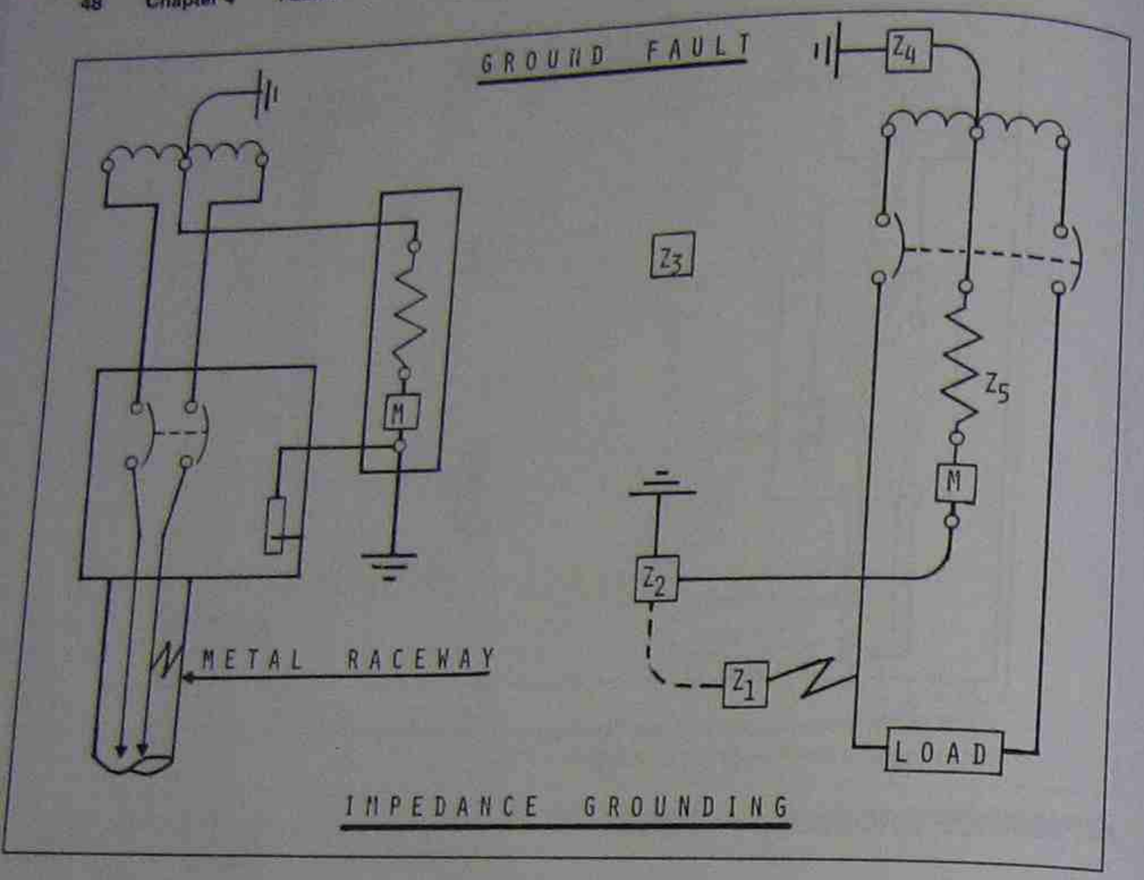


Fig. 4–9 Wiring diagram and one-line diagram—impedance grounding.

other uses. Impedance grounding acts very much in the same way by limiting current flow.

The impedance resistor is connected in series with the grounding electrode conductor, the neutral, the system overcurrent protective device, and the fault. Figure 4–10 illustrates the fault current flow for an impedance-grounded system. A wiring diagram and a simplified one-line diagram are used to illustrate the impedance controlling the current flow in a series circuit.

The flow of current starts at L_2 of the transformer, continues to the line side of the overcurrent protective device, goes through the overcurrent protective device, and travels on the conductor to the fault. After traveling through the fault, it goes to the steel raceway, through the metal raceway to the metal enclosure, through the bonding jumper to the ground bar, and then through the equipment grounding conductor to the grounding resistor and monitoring equipment. From there, the current goes through the grounding impedance, through the neutral to the center tap of the transformer, and through the transformer to L_2, which completes the series circuit.

Article 250 permits impedance grounding of systems operating at less than 1000 volts with some specific requirements. It also requires impedance grounding as one method of grounding systems supplying portable or mobile equipment.

UNGROUNDED SYSTEM FAULTS

Figure 4–11 illustrates what might be considered a three-phase, 480-volt or three-phase, 240-volt, three-wire system. There is no established ground at the utility transformer. There is a grounding electrode conductor and a grounding electrode system installed with the service, basically to maintain all metal enclosures at zero or ground potential.

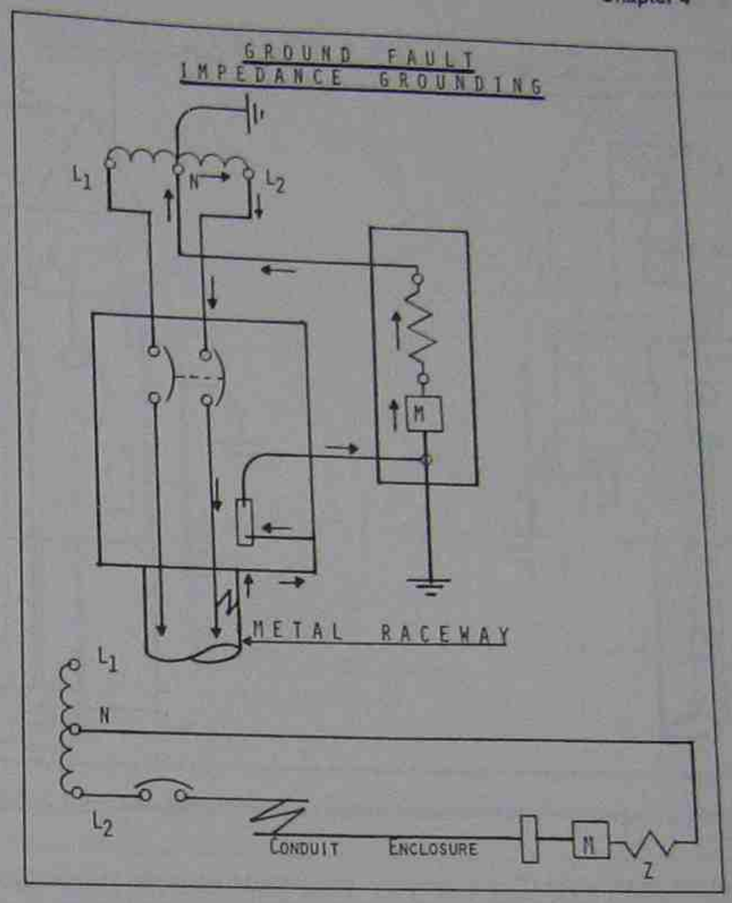


Fig. 4–10 Wiring diagram and one-line diagram—ground-fault impedance grounding.

This is a popular installation where only power is needed. Even though there is no grounded conductor, the Code still requires establishing a grounding electrode system and installing an equipment grounding system.

When there is a phase-to-phase fault, the overcurrent protective device reacts very quickly, because there is a very low impedance path for the current to flow on. When a ground fault happens, the result is completely different. When this type of fault occurs, for example on phase A as shown in Figure 4–12, nothing that can be readily seen happens. There is no current flow path directing the current back through the overcurrent protective device, which would activate the device. There is no complete circuit for the fault current to flow on, so nothing happens and a hazard is created. There must be a second ground, on a different phase, before there is a complete circuit for the current to flow on and cause the overcurrent protection device to operate.

There are some unseen and dangerous things that have taken place. Remember, the enclosure has been grounded to keep it at ground potential. The enclosures are now at the same potential as phase A, and phase A is now at ground potential. This means that a voltage now exists between phase B and any enclosure and phase C and any enclosure. Because a grounding electrode system has been established and an equipment grounding system has been installed, voltage to ground and the voltage between phases are the same.

For example, consider the system to be a three-phase, 480-volt, three-wire delta system,

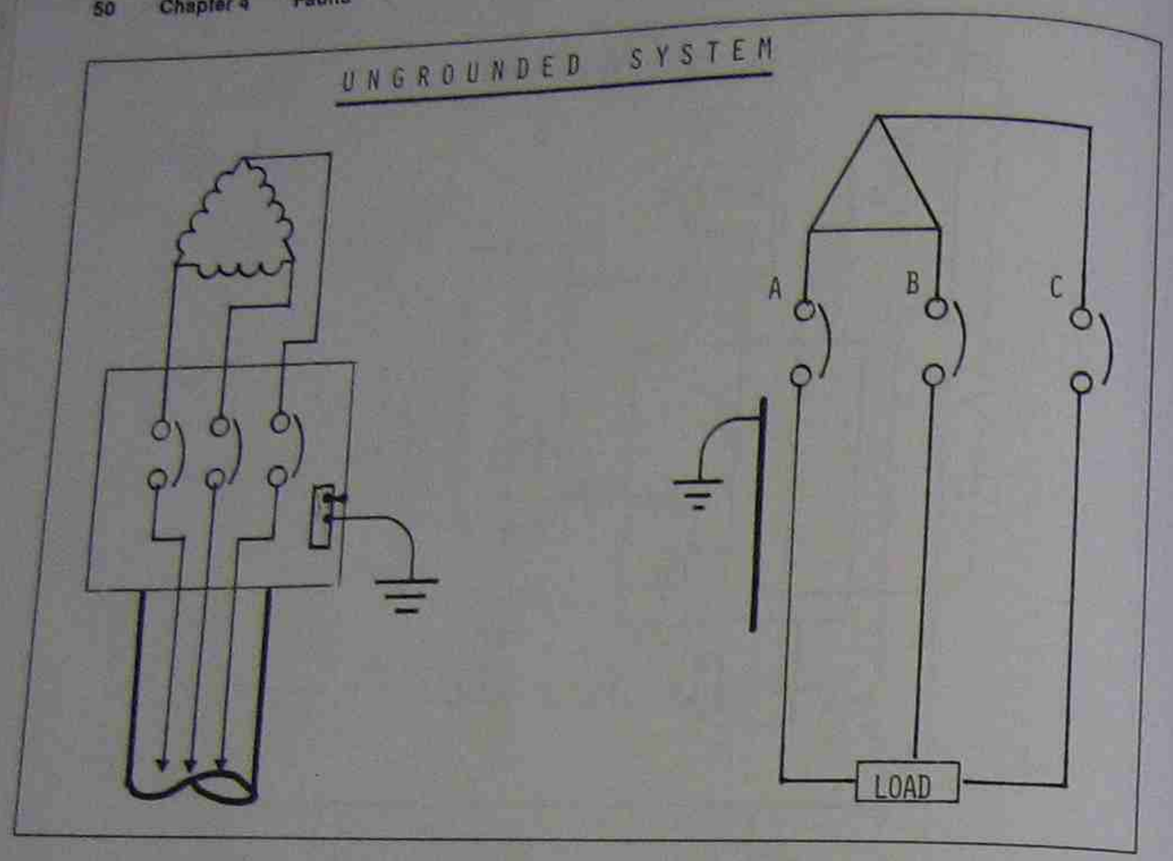


Fig. 4–11 Ungrounded system—three-phase, three-wire delta—no-fault situation.

with a ground fault on phase A, as illustrated in Figure 4–12. The following voltages would then exist: All phase-to-phase voltages will still be 480 volts.

Phase A to ground	zero volts
Phase B to ground	480 volts
Phase C to ground	480 volts

Figure 4–13 illustrates what happens when a second ground fault appears on phase C. Now there is a complete path for the current to flow on. Starting at the source of supply through phase A, the current flows through the overcurrent protective device to the fault, from the fault to ground, through the ground to the ground of phase C, through phase C, through the overcurrent protective device, and back to the source of supply. Now that the second fault has taken place, the overcurrent protective device has a chance to operate.

Whether or not it will operate depends on the impedance of the circuit through the ground path. If the impedance is low, the device will operate nearly as quickly as it would in a direct-short situation. If the impedance is high, the overcurrent protective device will look at it; treat it as if it were just a single-phase, phantom load in the overall circuit; and not operate. Depending on the size of the regular connected load, the overcurrent protective device will read the phantom load as just more load and furnish current to it accordingly until the current that is demanded exceeds the rating of the overcurrent device. More often than not, the impedance of the second ground is low enough to cause the overcurrent protective device to operate.

Figure 4–14 illustrates a three-phase, four-wire system with a ground fault on both phase A and phase C. There is a lot of distance in the ground path from the fault on phase A to the fault on phase C, and under these conditions it is likely that the overcurrent protective device will not operate.

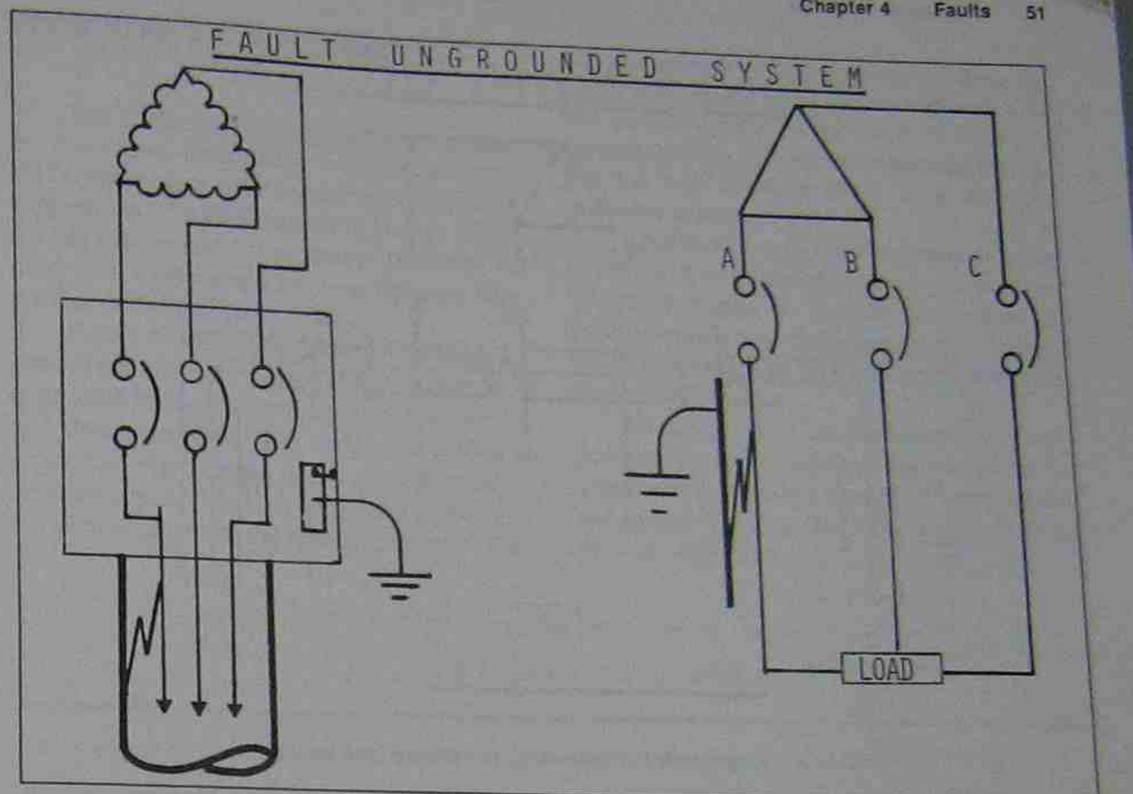


Fig. 4–12 Ungrounded system—three-phase, three-wire delta with first ground fault.

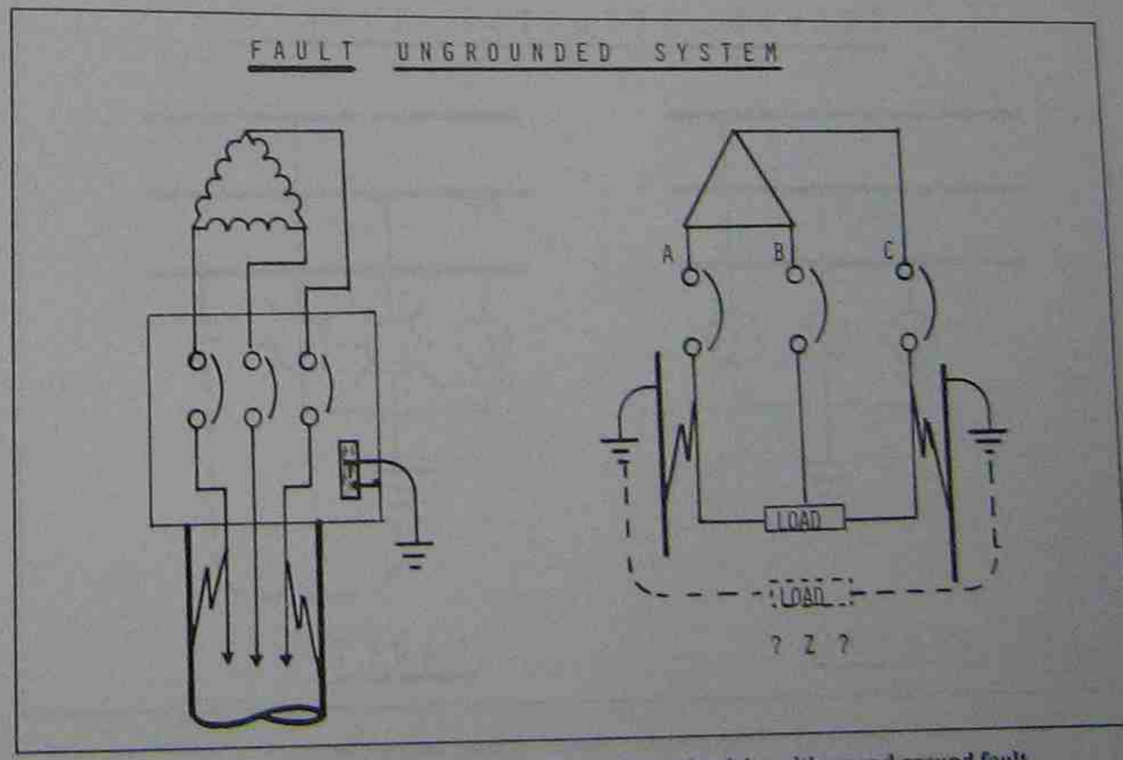


Fig. 4–13 Ungrounded system—three-phase, three-wire delta with second ground fault.

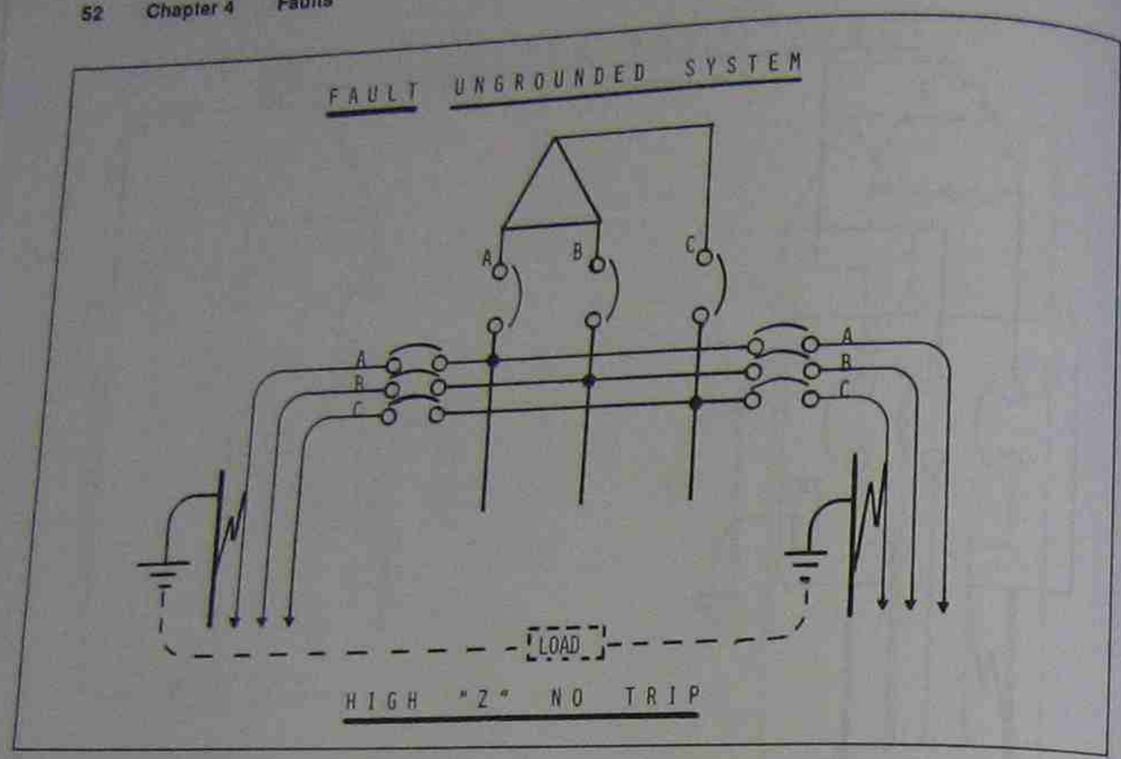


Fig. 4–14 Ungrounded system—high impedance fault no trip.

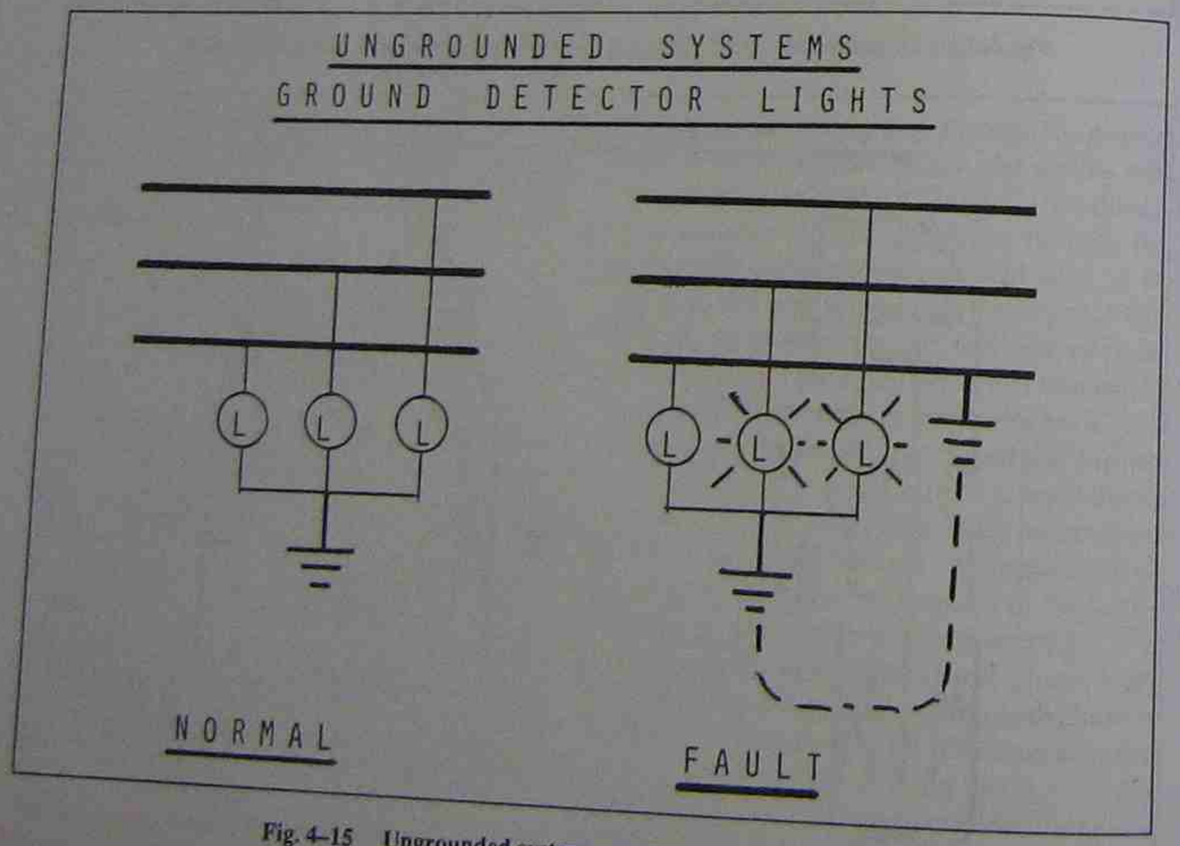


Fig. 4–15 Ungrounded systems—ground detector lights.

GROUND FAULT DETECTORS

The Code does not make recommendations, but gives information in Fine Print Notes (FPN) that is often taken as recommendations or suggestions. The FPN following *Section 250-5 (b) (4)* recommends that ground detectors be used with ungrounded systems because they provide additional protection.

Figure 4–15 illustrates the use of lights as ground fault detectors. Each phase conductor is connected through a lamp to a wye connection and then grounded. This really establishes a ground so that when a phase goes to ground, creating a ground fault, it completes a circuit to the grounded part of the wye at the lamps. This provides a circuit through the lamp and the lamp lights up, which indicates there is a ground fault and something should be done to clear it. Ground detector systems are often used in conjunction with any three-phase, three-wire ungrounded system.

Another alternative to the ground detector lights is to ground one of the three phases at the source of supply, so that the first ground is established. When the second ground takes place, it is hoped that the overcurrent protective devices will operate.

Grounding does not keep faults from happening. Proper grounding, however, works to create a low-impedance path for current flow and to limit the time that the hazard caused by the fault will exist.

CHAPTER 5

Grounding Electrode System

This chapter focuses on the grounding electrode system (figure 5–1). We will look at some grounding theory, types, and specifications for installing grounding electrodes and grounding electrode systems.

GROUNDING THEORY

The term *electrode* means "a way in or a way out for electricity." This term is used to identify the terminals of a battery that indicate the path for electricity to travel in and out of the battery. That electricity is made up of the electrons moving in and out of the battery.

The grounding electrode of an electrical installation is the way into the earth for the electrons. Therefore, installing a grounding electrode in the earth means installing an electrical terminal to help the electrons travel into the earth.

The 1978 Code changed the title of Part H of *Article 250* from "*Grounding Electrode*" to "*Grounding Electrode System,*" a major change that resulted in many changes to Part H. Prior to that time it was known as the "grounding electrode," and one grounding electrode was sufficient. The change from a single grounding electrode to a grounding electrode system has been

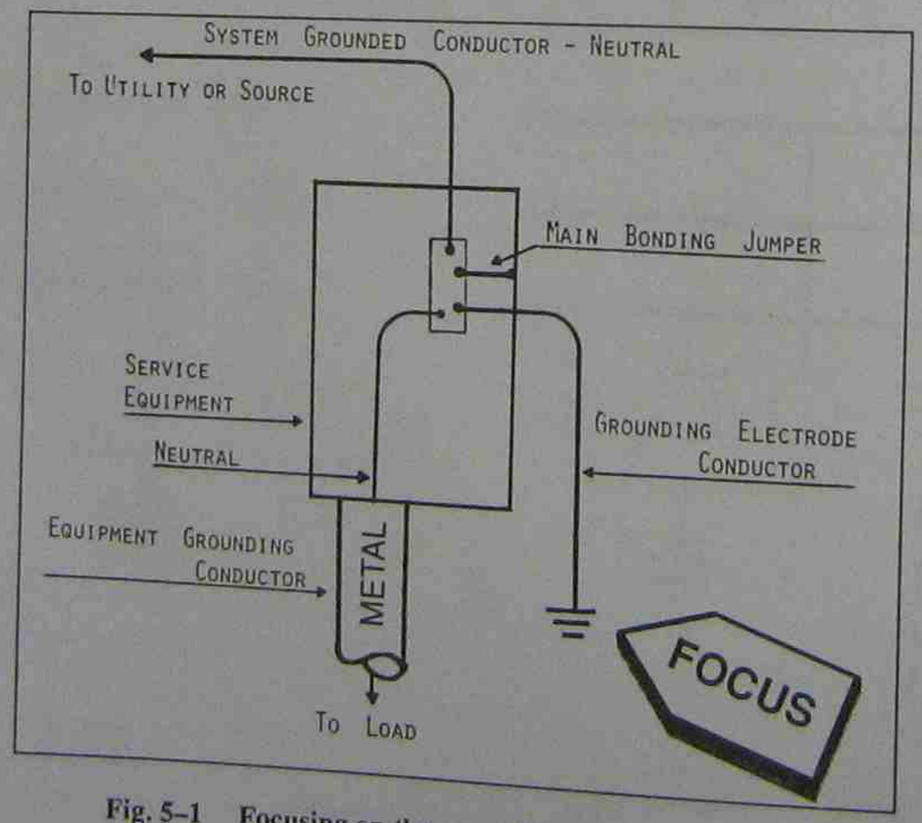


Fig. 5–1 Focusing on the grounding electrode system.

SOME DOWN-TO-EARTH FACTS ABOUT OLD MOTHER EARTH

EARTH IS ZERO POTENTIAL.

EARTH IS A CONDUCTOR.
NOT THE BEST, BUT NEVERTHELESS A GOOD ONE.

EARTH IS A VERY LARGE CONDUCTOR.
CONDUCTOR LENGTH – VERY LONG
CONDUCTOR CROSS-SECTIONAL AREA – VERY WIDE

EARTH'S CONDUCTIVITY VARIES WITH
TYPE OF SOIL
TEMPERATURE AND TIME OF YEAR
MOISTURE CONTENT
BURIED TRASH
INSULATING OR CONDUCTING MATERIALS

EARTH IS GROUND – GROUND IS EARTH.

Fig. 5–2 Some facts about Old Mother Earth.

with both the season of the year and the temperature.

the electron flow by installing conductors and

ground rod and the resistance around it. There

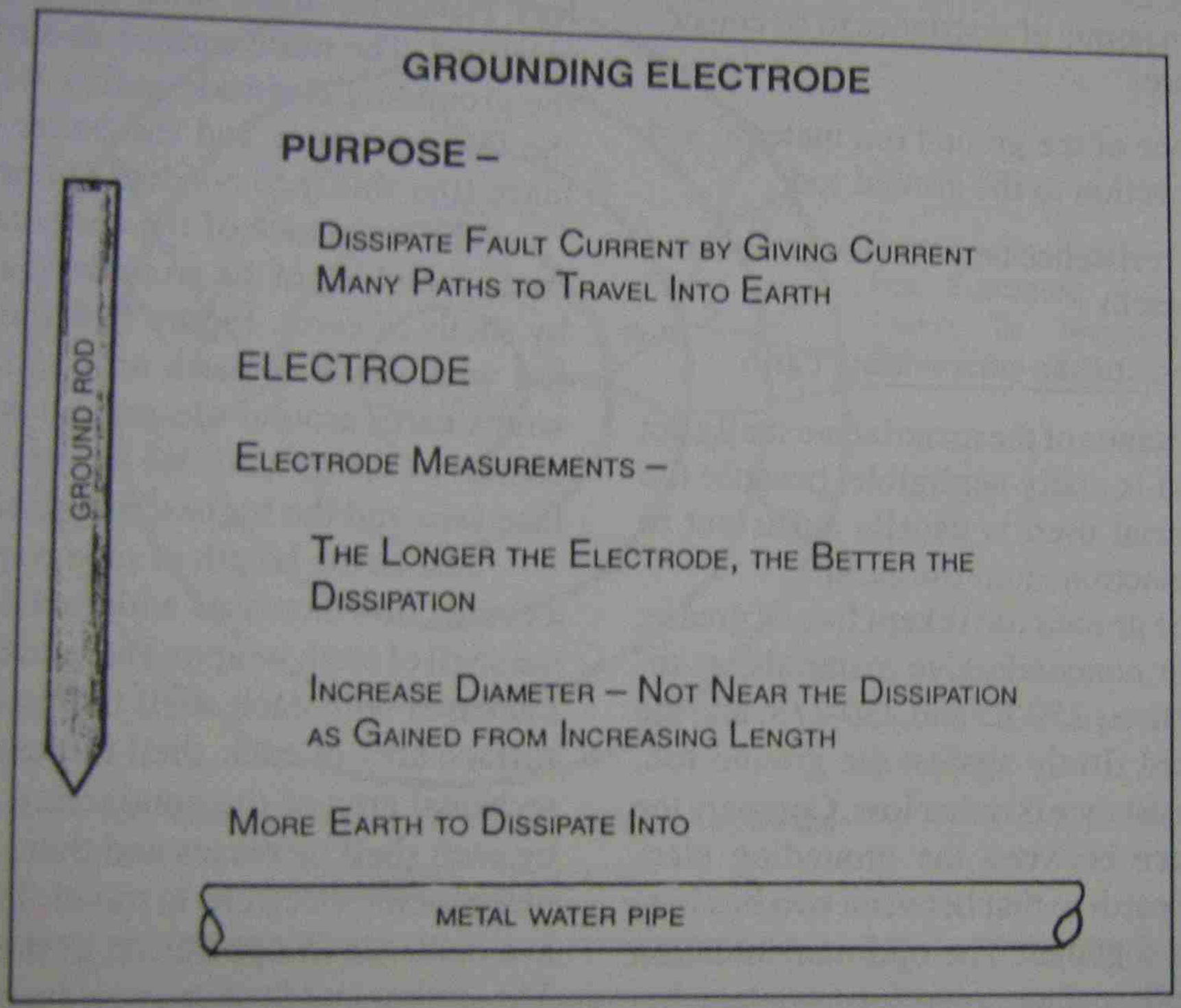


Fig. 5–3 Purpose and length of the grounding electrode.

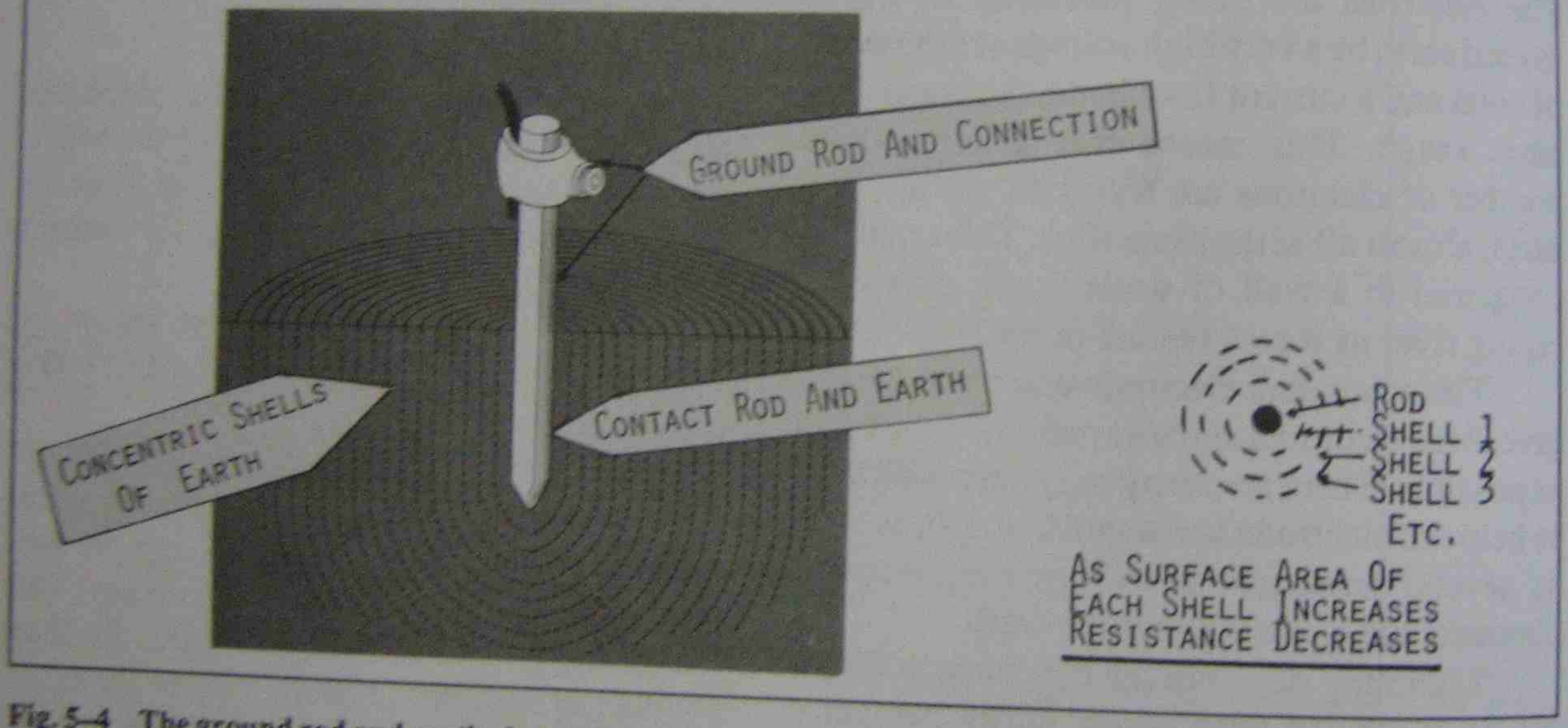


Fig. 5–4 The ground rod and earth electrode resistance. Earth shells are formed around the electrode. Courtesy FL Blackburn.

are three main points of resistance to be considered. These are:

less resistance there will be to the flow of electrons. The more surface to surface contact

same thing. Imagine that this illustration is one

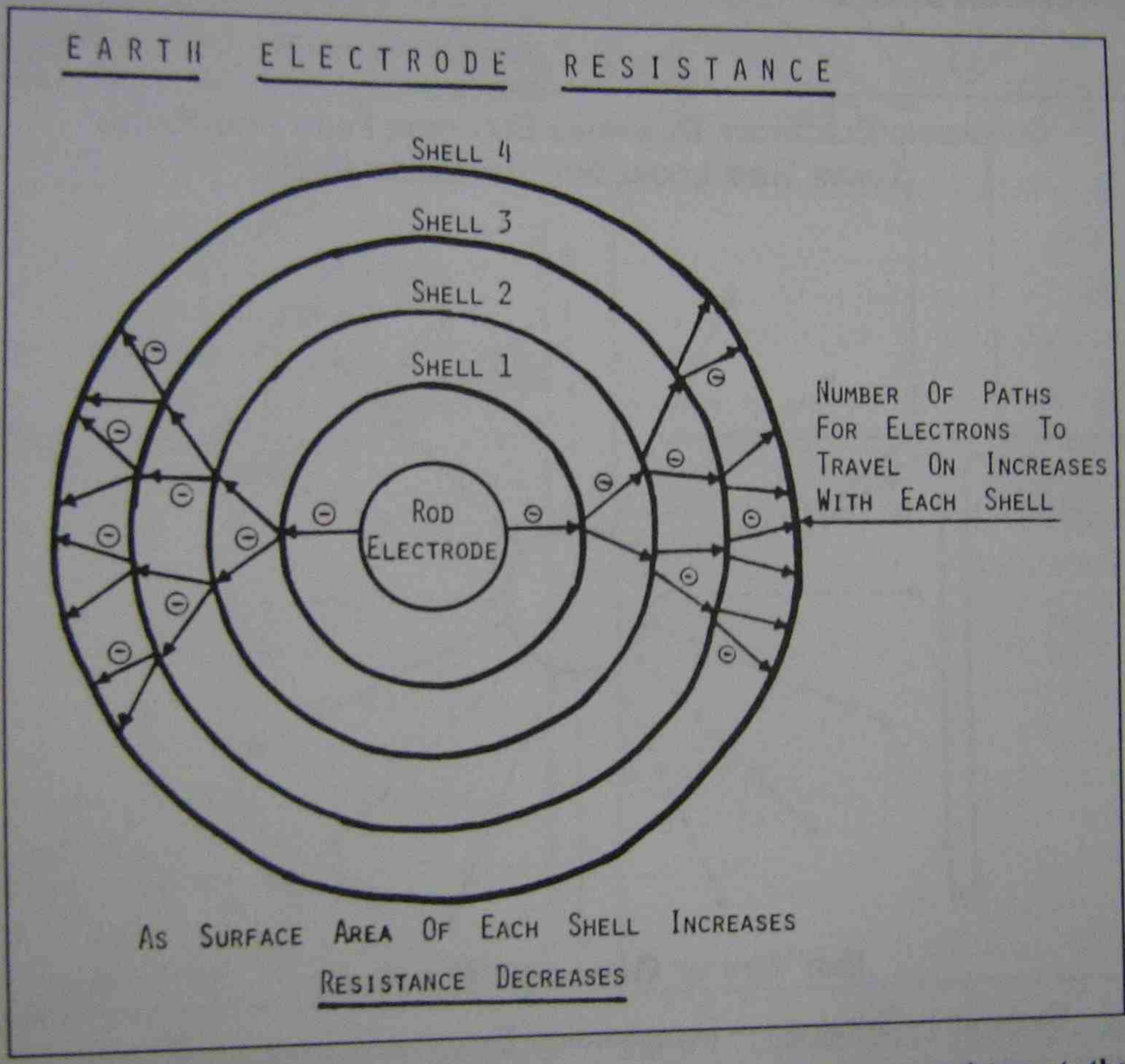


Fig. 5–5 The shells form an increasing number of paths and decrease resistance to the flow of current.

than through ground. When a grounding electrode is installed for computer grounding, it shall be bonded to the existing grounding elec-

6. Shall not rely on water meters for bonding connection to interior metal water piping.

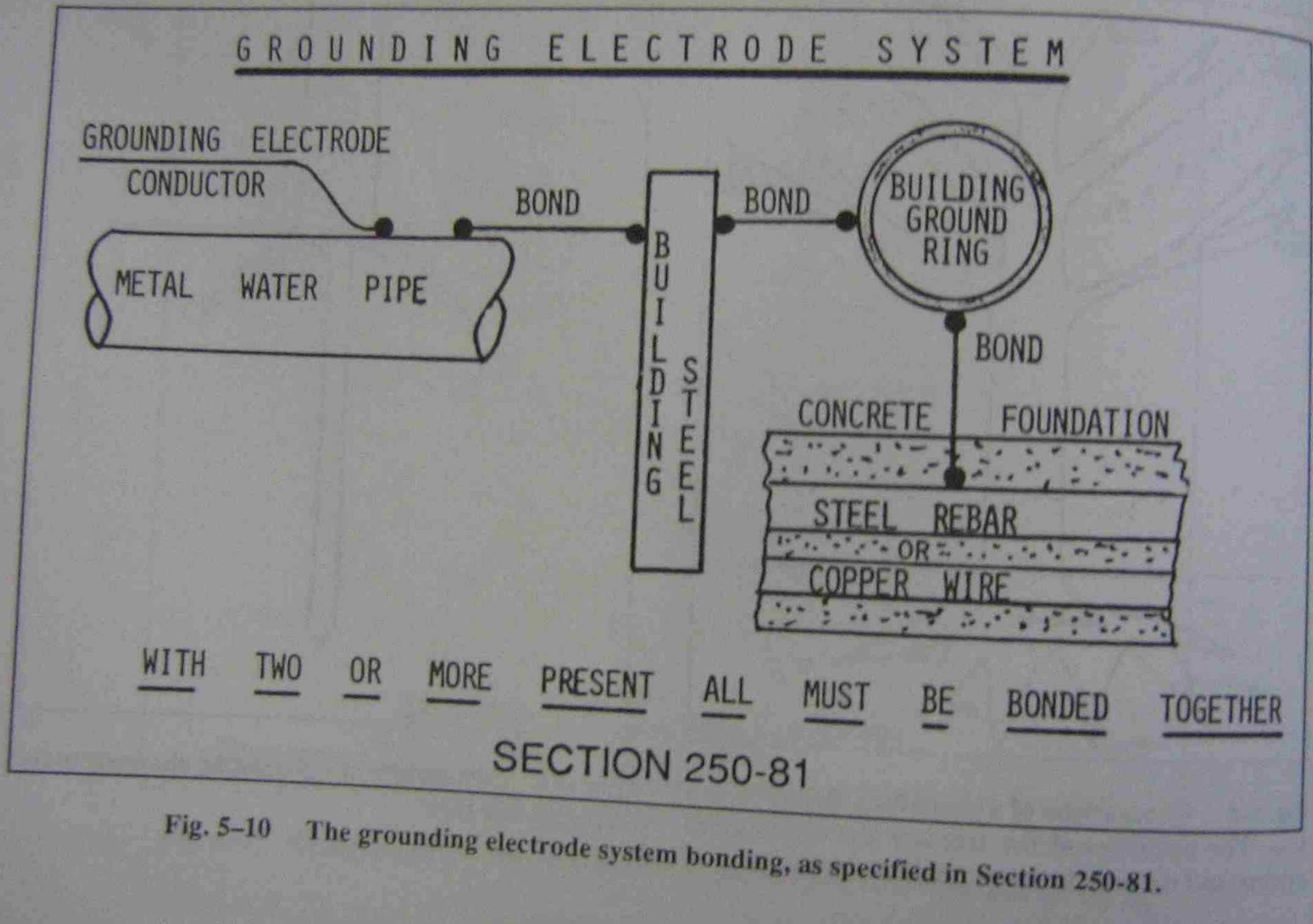


Fig. 5–10 The grounding electrode system bonding, as specified in Section 250-81.

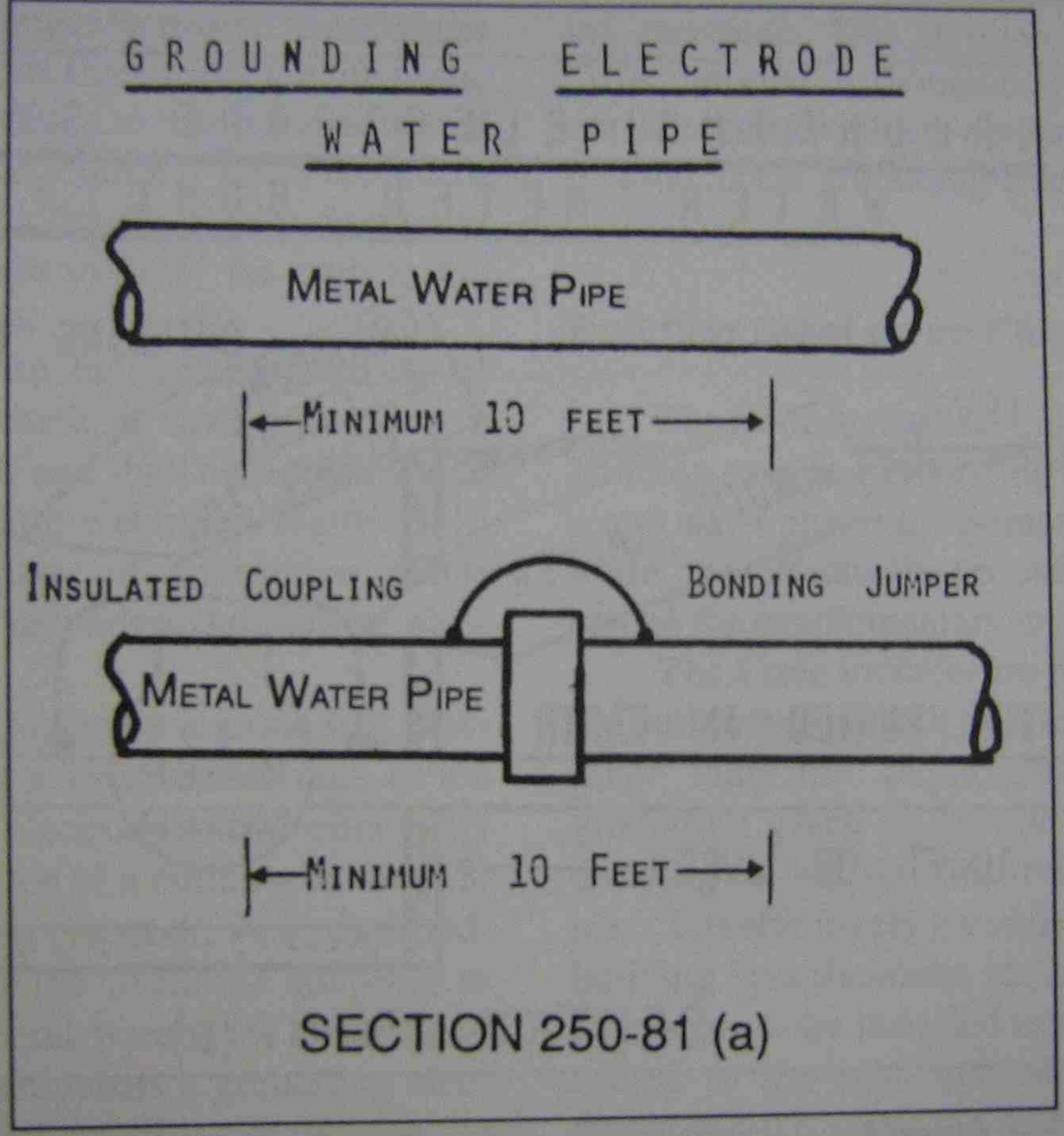


Fig. 5–11 Requirements for a grounding electrode water pipe.

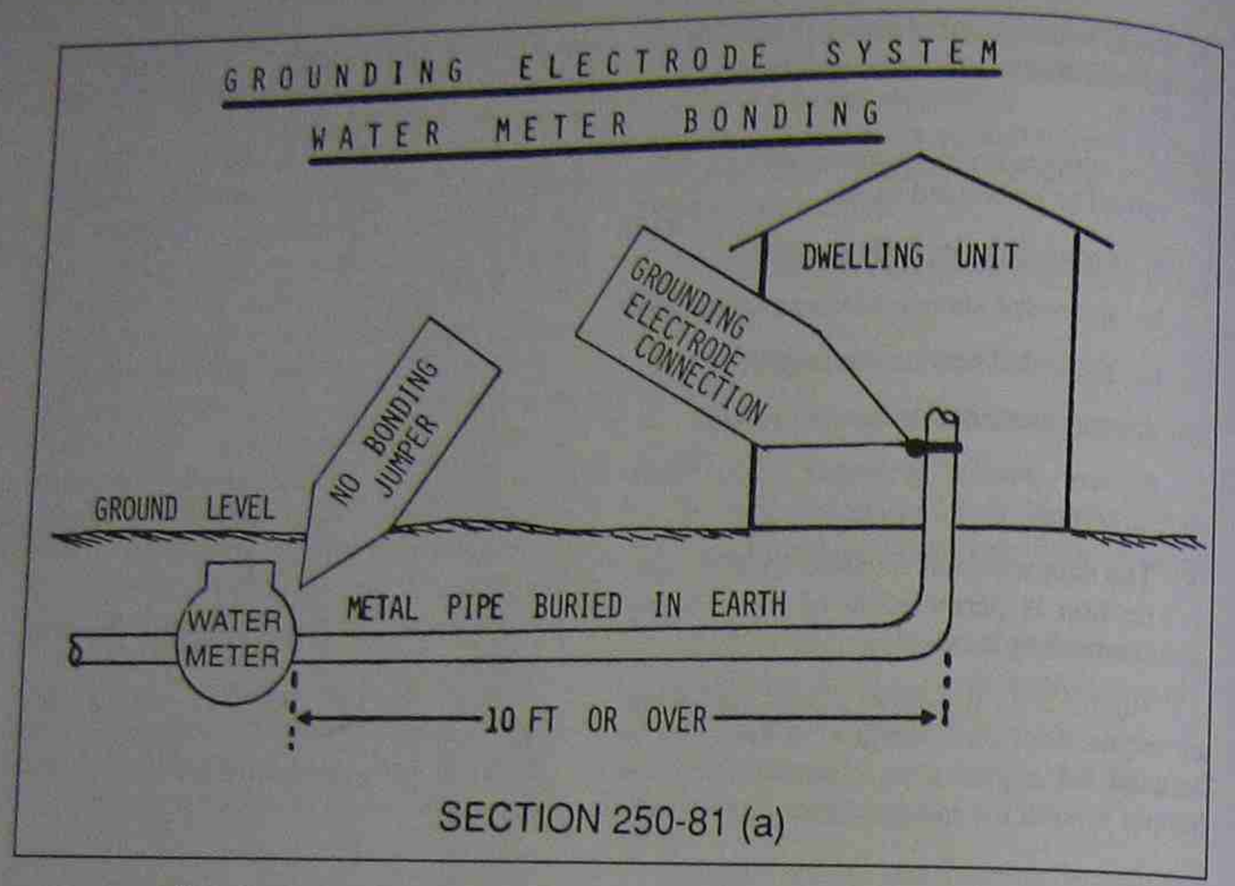


Fig. 5–12 Requirements for a grounding electrode system with a water meter.

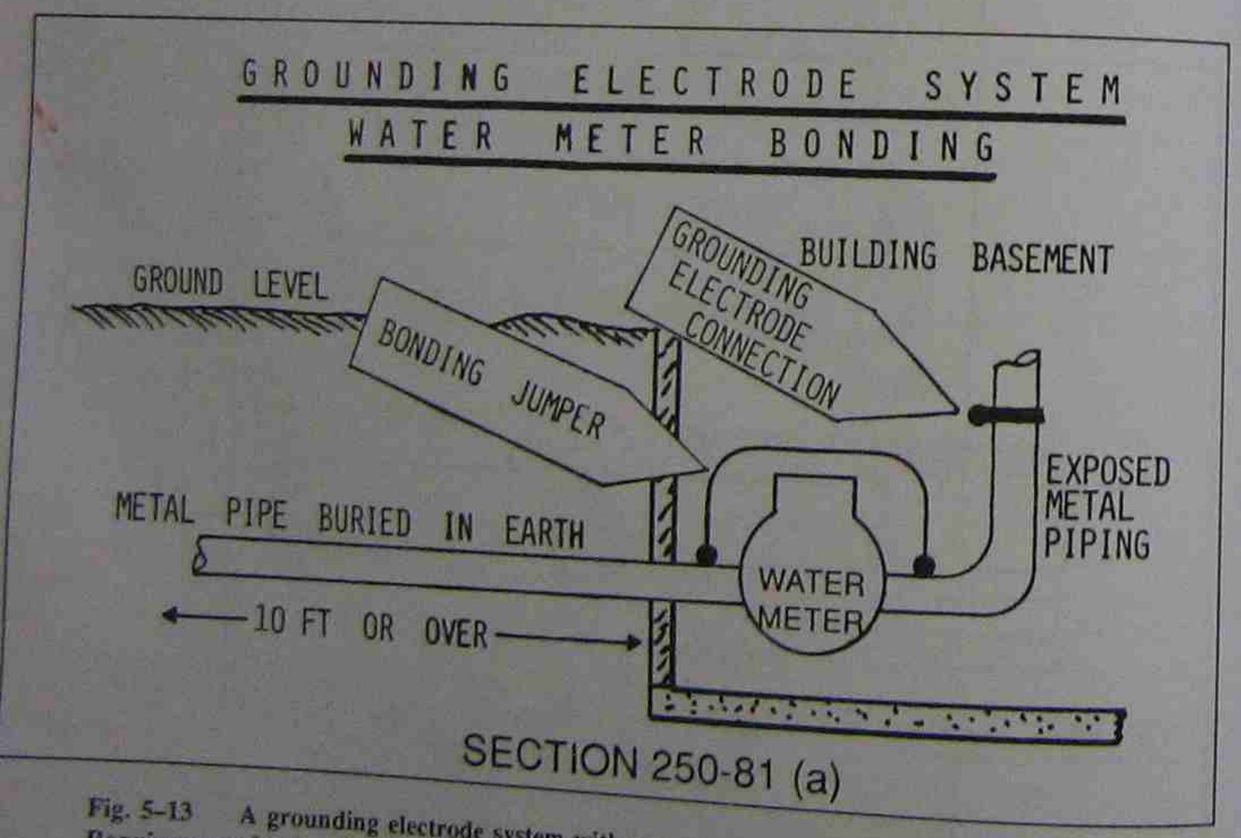


Fig. 5–13 A grounding electrode system with a water meter installed inside a building. Requirements for bonding.

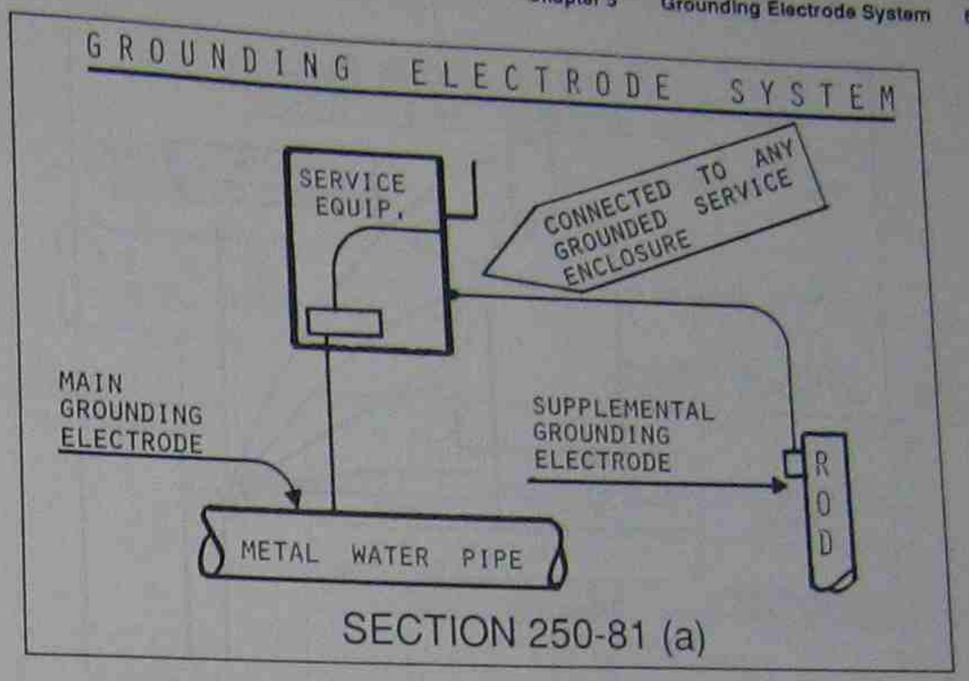


Fig. 5–14 A grounding electrode system using a water pipe and a ground rod.

Reason: The thought here is that the metal water pipe can no longer be trusted to remain as a grounding electrode throughout the life of the installation. It is too easy to take out a section of metal water pipe and replace it with a section of plastic pipe, thereby destroying the continuity of the grounding electrode or the path to the grounding electrode.

However, when the underground metal water piping is present, it shall be used as a grounding electrode and shall be supplemented by another grounding electrode. Figure 5–15 illustrates a multitude of connection points permitted for the secondary grounding electrode.

Figure 5–16 illustrates a grounding electrode system using a metal water pipe as the primary grounding electrode and the effectively grounded metal frame of a building as the supplemental grounding electrode. Note the bonding jumper around the insulated coupling to ensure 10 feet of metal-water-pipe electrode.

Figure 5–17 illustrates a grounding electrode system using a metal water pipe as the primary grounding electrode and a concrete-encased electrode as the supplementary grounding electrode. This is often referred to as "Ufer" ground. Although both the rod and wir are illustrated, both are not required. Either ca be used as the grounding electrode.

Building Steel as an Electrode

The Code recognizes effectively ground building steel as a grounding electrode. Whe metal water pipe is the primary grounding el trode, the effectively grounded building st can be the supplementary grounding electro

The Code includes no provisions on h the building steel shall be effectively ground other than the requirements for effect grounding given in *Section 250-51*. Whe building is set on steel-reinforced conc piers, it is effectively grounded. However, s building specifications require a bare co conductor to be installed in the piers and nected to the steel columns. The desig engineer determines the size and length o copper conductor.

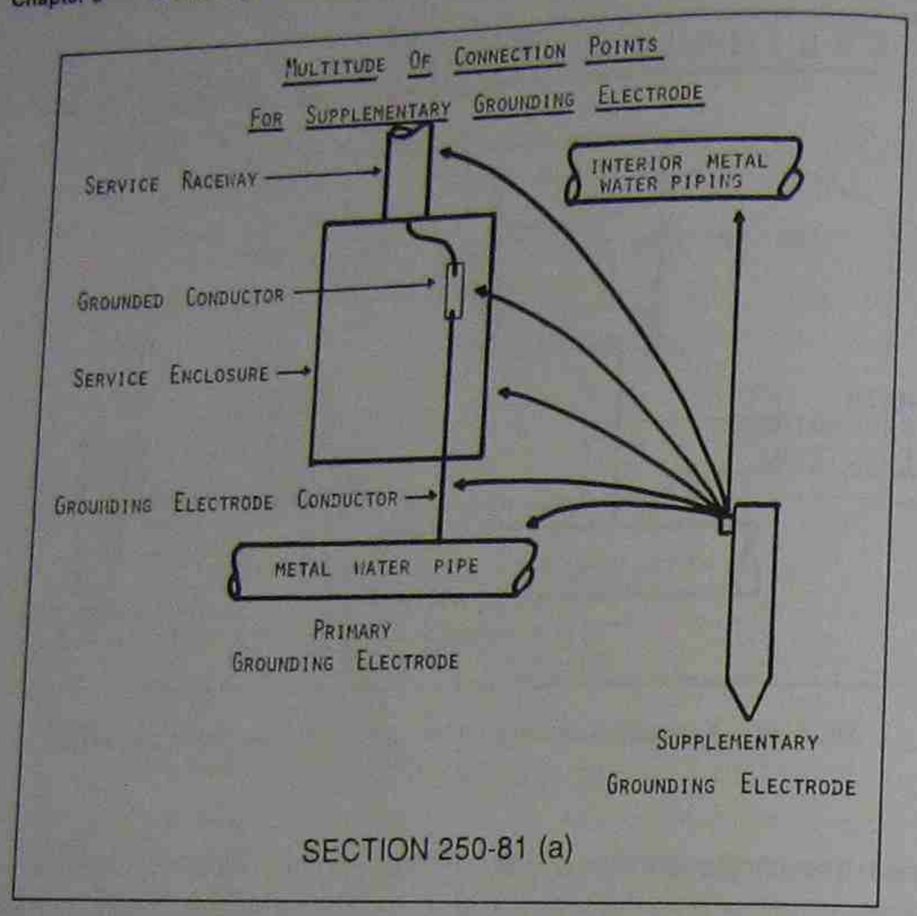


Fig. 5–15 The multitude of connections allowed for a supplementary grounding electrode.

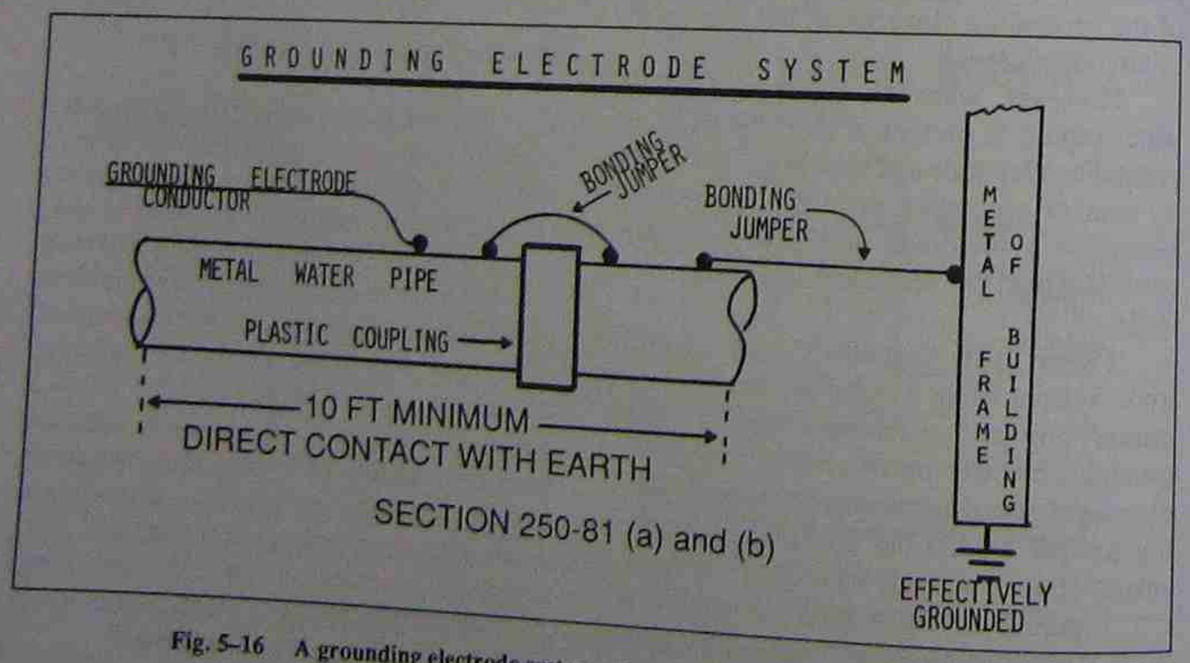


Fig. 5–16 A grounding electrode system using a water pipe and building steel.

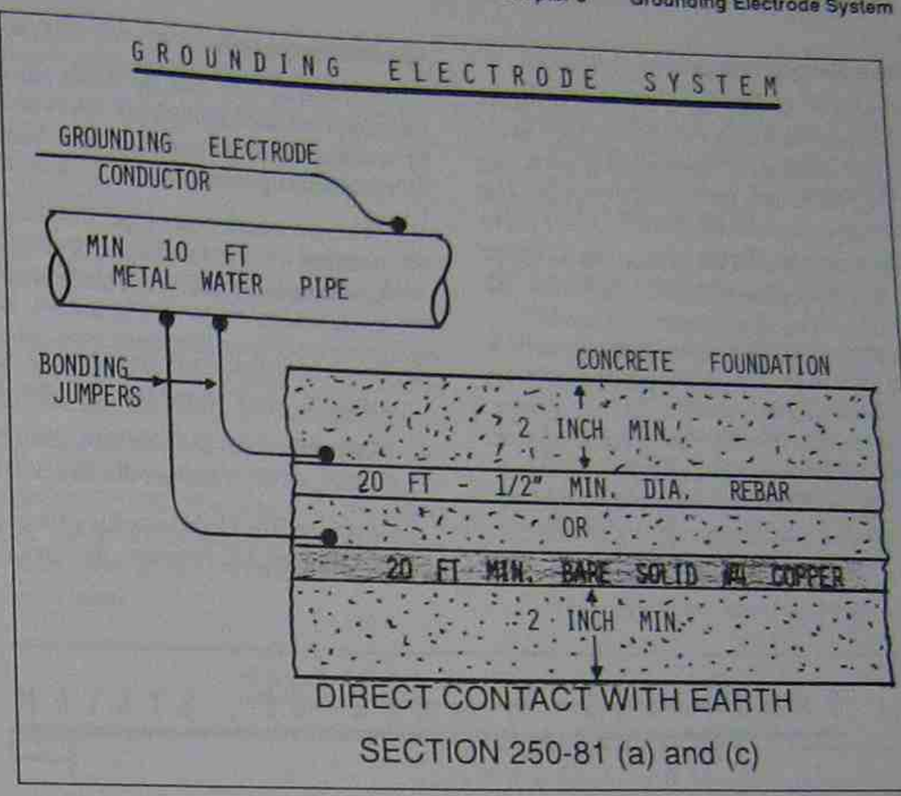


Fig. 5–17 A grounding electrode system using a water pipe and a concrete-encased electrode.

Concrete-Encased Electrode

Section 250-81(c) (Concrete-Encased Electrode) allows the use of either one or more reinforcing bars (rebars) or a copper conductor, sized as specified in figure 5–17, encased in at least 2 inches of concrete. In addition, the concrete must be in direct contact with the earth.

The concrete-encased grounding electrode is becoming more and more popular. If you have ever had to break up some concrete, you may have noticed how the concrete clings to the steel rebar. This could indicate that there is a very good surface-to-surface contact between the grounding electrode and the concrete encasing it. The rebar can also offer many parallel paths for the electrons to travel on, thereby decreasing the impedance of the ground path.

The concrete-encased electrode has several advantages. These include:

1. Concrete in contact with the earth tends to retain moisture.
2. A rebar could offer more than one path for electron flow.
3. The weight of the building maintains a steady pressure at the point of connection between the concrete and the earth.
4. The concrete provides a large surface-to-surface contact with the earth.
5. Many tests made with the concrete-encased electrode have proven it to be a very steady and successful grounding electrode.

Caution: When a vapor barrier, such as plastic, is used between the concrete and the earth, the concrete is no longer in direct contact with the earth and the value of the earth-to-concrete connection is destroyed. In this case, it could not be used for a concrete-encased electrode.

The Code considers concrete a grounded surface and so states in *Section 110-16 (a).*

Ground Ring Electrode

Figure 5–18 illustrates a grounding electrode system that uses a metal water pipe as the primary grounding electrode and a ground ring as the supplementary grounding electrode. The ground ring is required by *Section 250-81 (d)* to be made of at least 20 feet of bare No. 2 copper and to be buried at a minimum depth of 2 1/2 feet.

A computer installation might specify a separate ground ring in addition to the existing grounding electrode installed for the power system. More often than not, the specification of the ground ring is more than the minimum specified by the Code. However, it still shall be bonded to other existing grounding electrodes for the building.

Made Electrodes

Section 250-83 lists the made electrodes; they are illustrated in figure 5–19. A sentence-by-sentence look at *Section 250-83* lists some very important points.

1. Where a metal water pipe, building steel, concrete-encased electrode, or ground ring is not available, one of the made electrodes can be used.
2. For best results, made electrodes should be installed below permanent moisture level.
3. Made electrodes shall be free from paint, enamel, or other nonconductive coatings.

Comment: The Code is looking for as good a contact as possible between the grounding

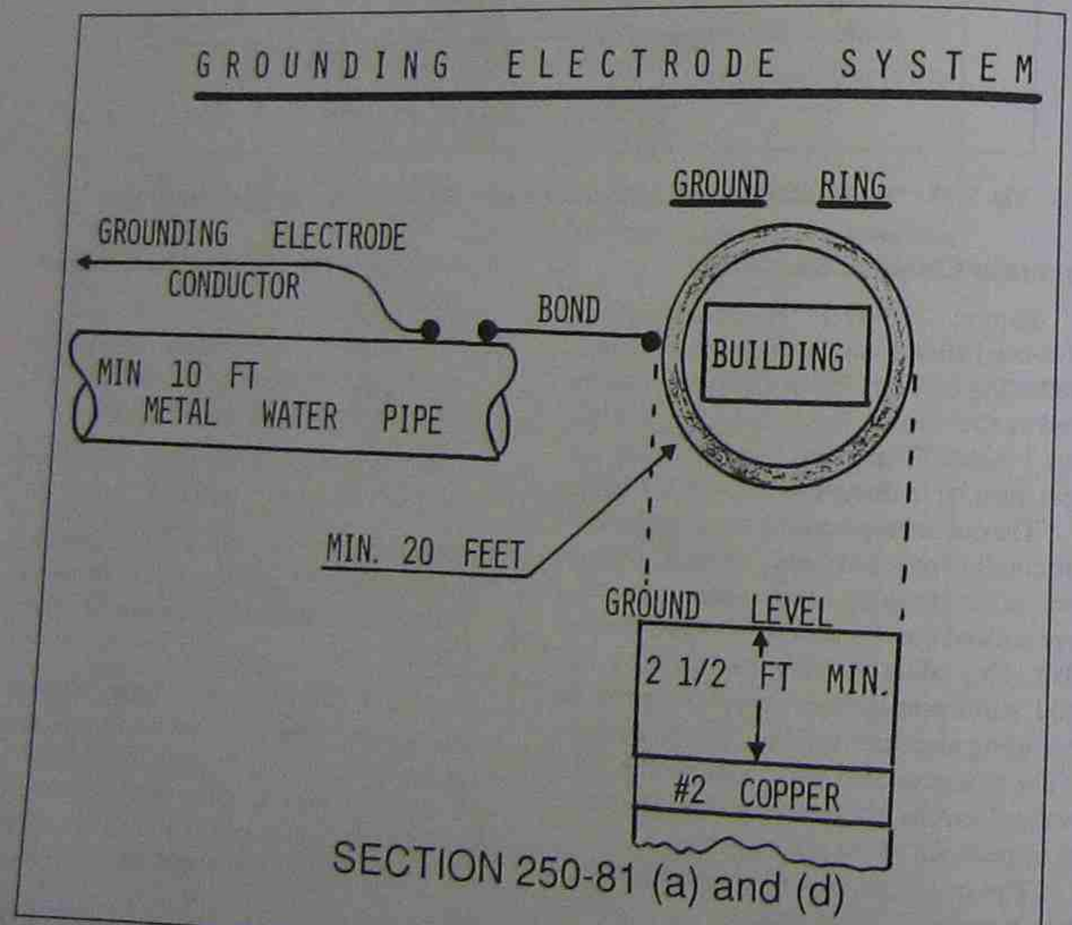


Fig. 5–18 A grounding electrode system using a water pipe and a ground ring.

electrode and the earth. Grease, paint, and enamel can be considered insulators.

4. Grounding electrodes shall be separated by at least 6 feet. This also applies to grounding electrodes used for lightning rod grounding.

Comment: A little earlier we looked at the ground rod and the earth shells around it. Now there is the regulation that when there are two electrodes, they shall be at least 6 feet apart. One thought here is that if the electrodes are too close together, the shells of earth around an electrode will overlap, thereby increasing the opposition to the electron flow into the earth.

Section 250-83 lists the four so-called made or other electrodes recognized by the Code and some of the requirements that go along with them.

1. Metal underground gas piping system and its important requirements. It must be electrically continuous, meaning it cannot be interrupted by insulating sections or joints. Insulated joints are often used in gas lines to break up continuity.

   The gas line cannot have an outer nonconductive coating. It is not unusual for the gas line to be wrapped with an insulating tape or covered with insulating material to combat electrolysis.

   The use of the gas line as a grounding electrode has to be acceptable to both the gas supplier and the authority having jurisdiction.

2. Other local metal underground systems. This could be an effectively grounded

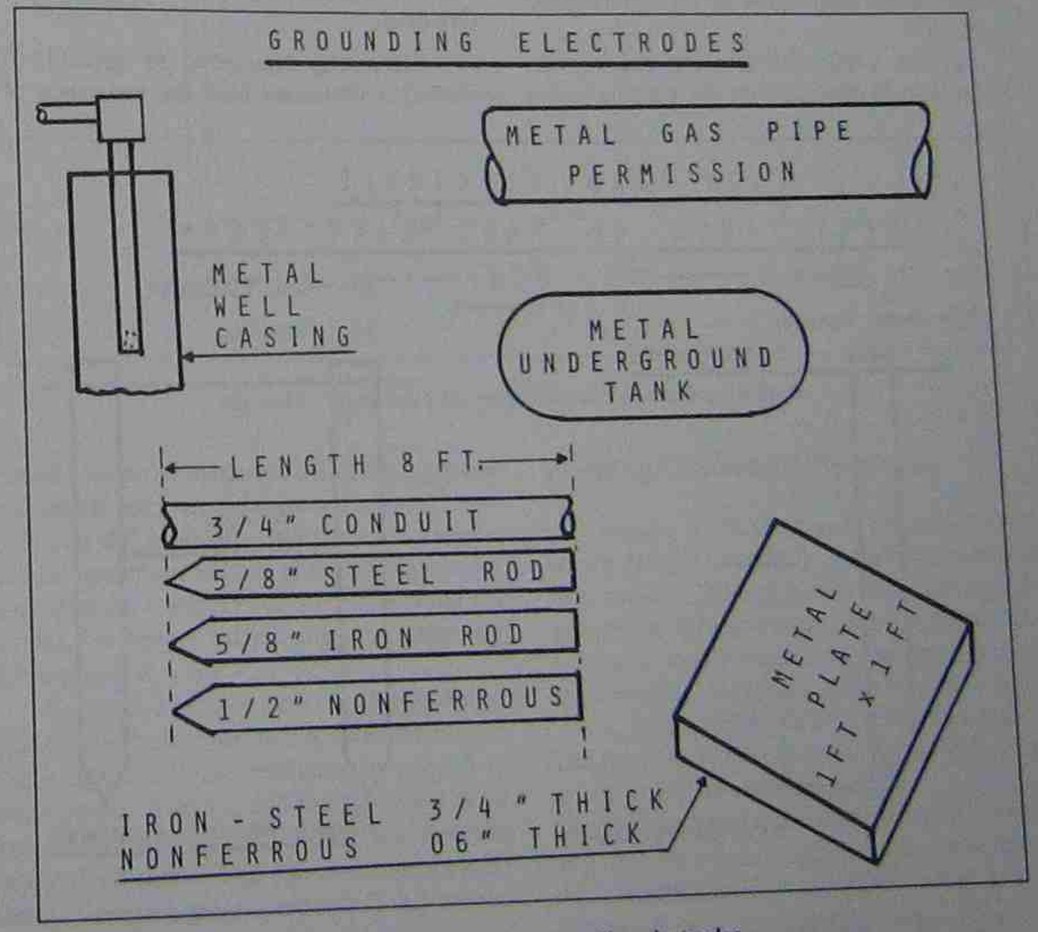


Fig. 5–19 Various grounding electrodes.

metal structure, a metal oil pipeline, or a metal underground storage tank. However, should any of these be used, all the provisions listed, such as no paint and good earth contact, will have to be fulfilled.

3. Rod and pipe electrodes.

Comment: This is the most commonly used of the made electrodes. Various types of rods or pipes are recognized for use as grounding electrodes. Figure 5–19 illustrates these pipes and rods and shows their size limitations.

4. Plate electrodes.

The size limitations for plate electrodes are also shown in figure 5–19. However, there is no specification listed for the depth at which the plate must be buried, other than in *Section 250-83*, which requires that when practicable, it should be installed below permanent moisture level.

Figure 5–20 illustrates the requirement outlined in *Section 250-84* for spacing made electrodes when the resistance is less than 25 ohms. Two electrodes is the maximum required. This section only applies to rod, pipe, or plate electrodes; when the second electrode is installed, both are bonded together and treated as a single electrode from then on. Once again the 6-foot measurement between electrodes is mentioned and the Fine Print Note (FPN) indicates that the efficiency will be even better if they are installed more than 6 feet apart. This will also help to keep the shells of earth around the grounding electrode from overlapping.

One grounding electrode system used with computer grounding consists of three ground rods located at each corner of a 10-foot triangle. They are then connected together as a grounding electrode system.

Grounding Electrode Resistance to Ground

Measuring resistance to ground (figure 5–21) illustrates how the resistance of a

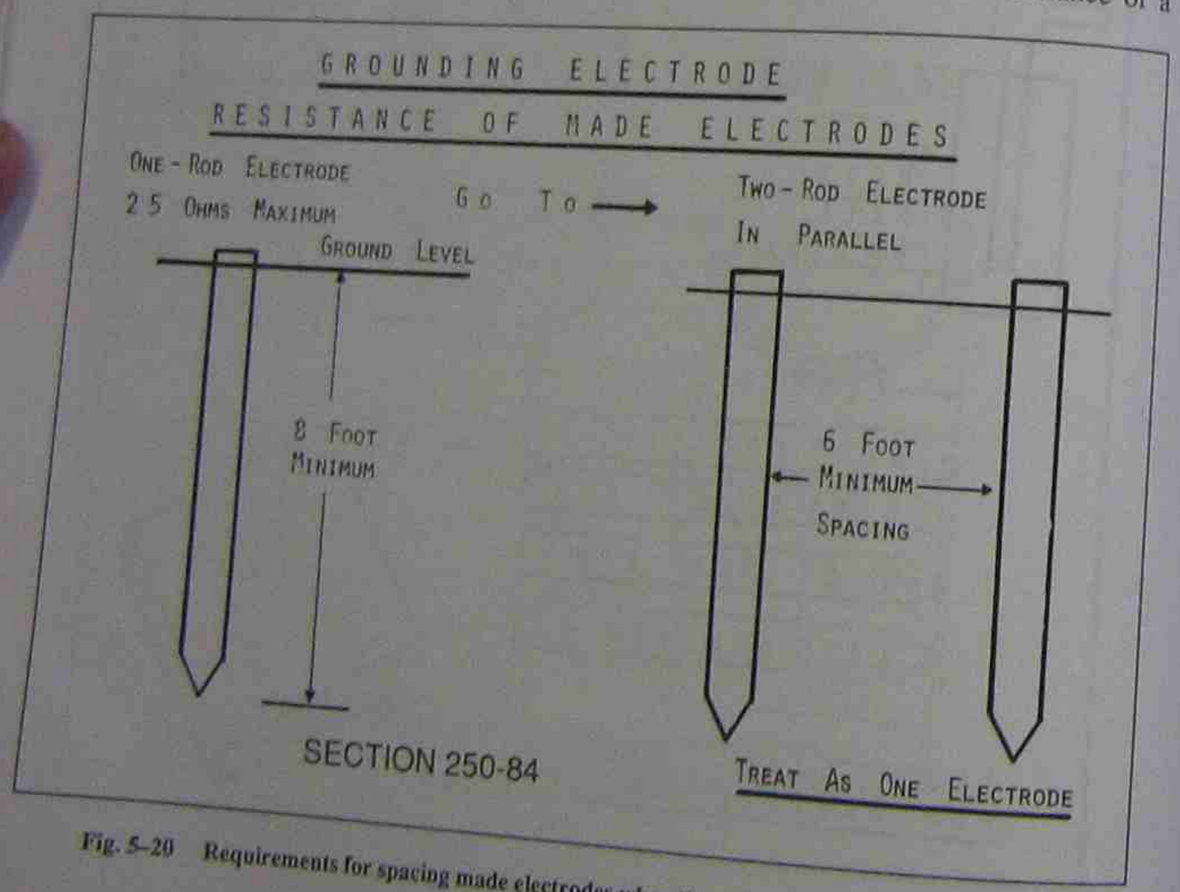


Fig. 5–20 Requirements for spacing made electrodes when the resistance is less than 25 ohms.

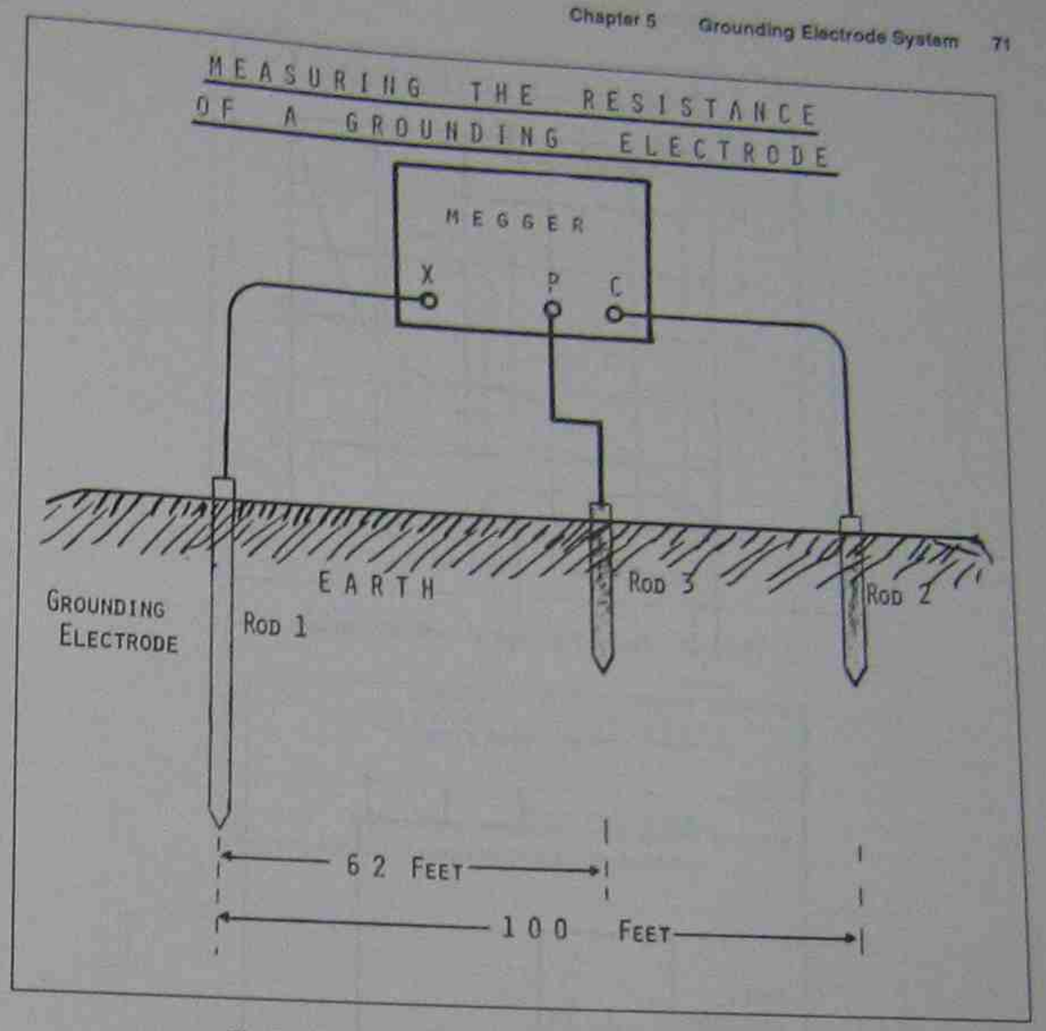


Fig. 5–21 Measuring the resistance of a grounding electrode.

ground rod can be measured using a megger (an instrument used to measure resistance), two rods, and the grounding electrode. A megger actually generates voltage and causes a current flow. When the voltage and the current flow are known, the megger will calculate the resistance (Ohm's law: $R = E/I$).

Figure 5–22 shows how the 62-foot measurement for the location of rod 3 was calculated. The graph charts the resistance to ground in ohms against distance and indicates that at 62 feet, there are 20 ohms, which is less than the required 25 ohms. Had this reading been 30 ohms, a second ground rod would have been required.

Bonding Grounding Electrodes

Figure 5–23 illustrates *Section 250-86*, which prohibits using a grounding electrode installed for a lightning rod system to be used for grounding wiring systems and equipment. The electrical supply must have a separate grounding electrode. However, as illustrated in figure 5–24, the grounding electrode for the lightning and the one for the electrical supply system are permitted to be bonded together.

Figure 5–25 illustrates the value of bonding together all separate grounding electrodes, as recommended by the FPN to *Section 250-86*. Doing so will limit the potential difference

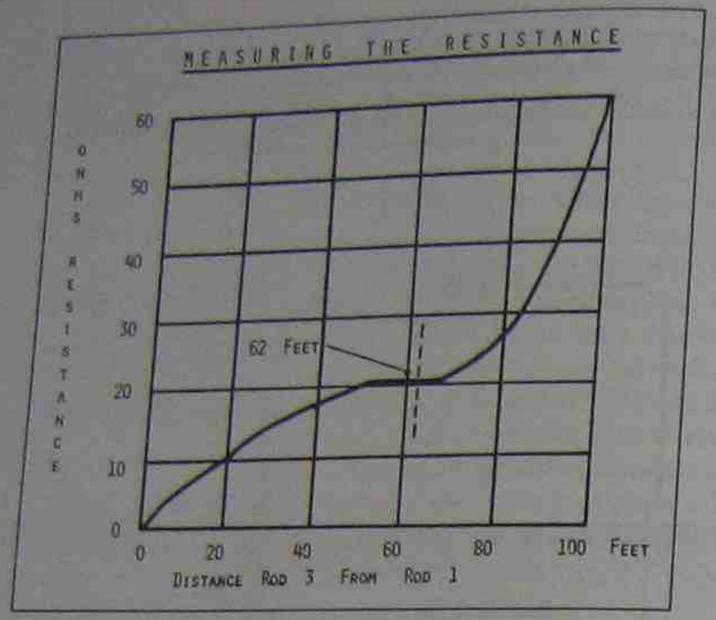


Fig. 5–22 Grounding electrode resistance graph.

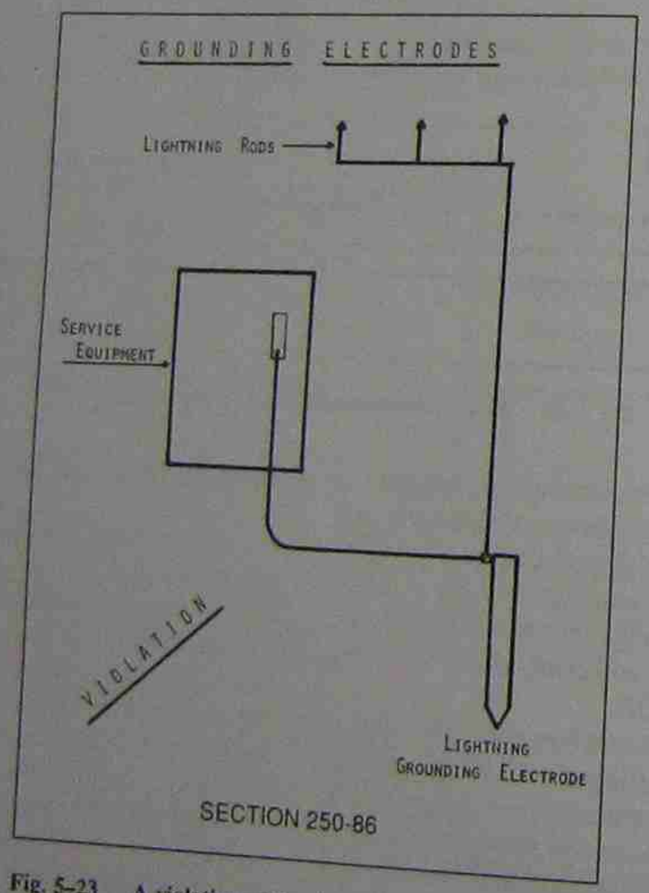


Fig. 5–23 A violation of *Section 250-86*, which prohibits using the same grounding electrode for a lightning rod system and a system supply.

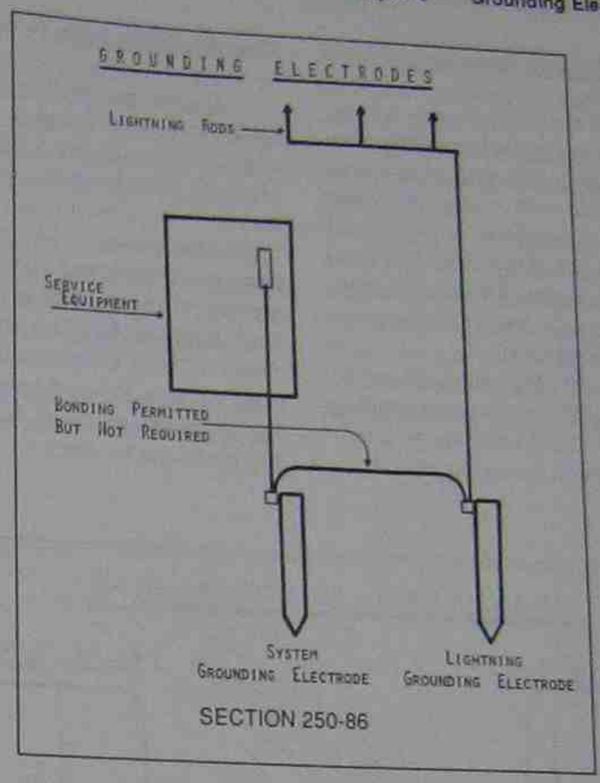


Fig. 5–24 Permitted connection of a system grounding electrode and a lightning rod grounding electrode.

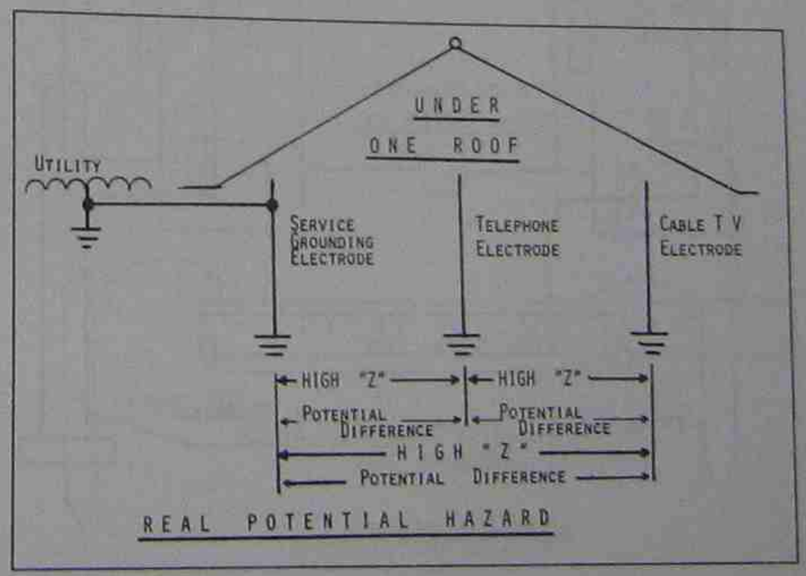


Fig. 5–25 When different grounding electrodes are used for a building and are not bonded together, a potential hazard will exist.

between them and between associated wiring of the different systems.

There are other electrical systems brought into a building that require a grounding electrode—the telephone system and cable television. Each is permitted to have its own grounding electrode. But to eliminate any potential differences between any of the grounding electrodes and any of the pieces of electrical equipment of each system, all the grounding electrodes should be bonded together.

Section 800-31 (b) (7) permits, where installed, the bonding of the telephone grounding electrode. *Section 820-22 (h)* permits the bonding of the cable television grounding electrode.

One Building with Two Services

The exceptions to *Section 230-2 (Number of Services)* permit more than one service to the same building. Figure 5–26 illustrates a building being served by two separate services. Each service is required to have a grounding electrode. One service uses a metal water pipe as the primary electrode and a ground rod as a supplementary electrode. The second uses the effectively grounded building steel for the grounding electrode. Both are acceptable grounding electrode systems. When the two different grounding electrodes are used, however, a potential difference can be detected between the enclosures of service number one and the enclosures of service number two. Therefore, this is a violation of *Section 250-54*, which requires that when a building is supplied by two or more services and a grounding electrode is required, the same grounding electrode shall be used for both services.

Reason 1: By using one common grounding electrode, the potential difference caused by lightning or external power faults will limit the potential difference on metal enclosures and raceways.

Reason 2: By using one common grounding electrode, the potential difference between grounding electrode systems of different electrical power sources that supply the same premises will be reduced.

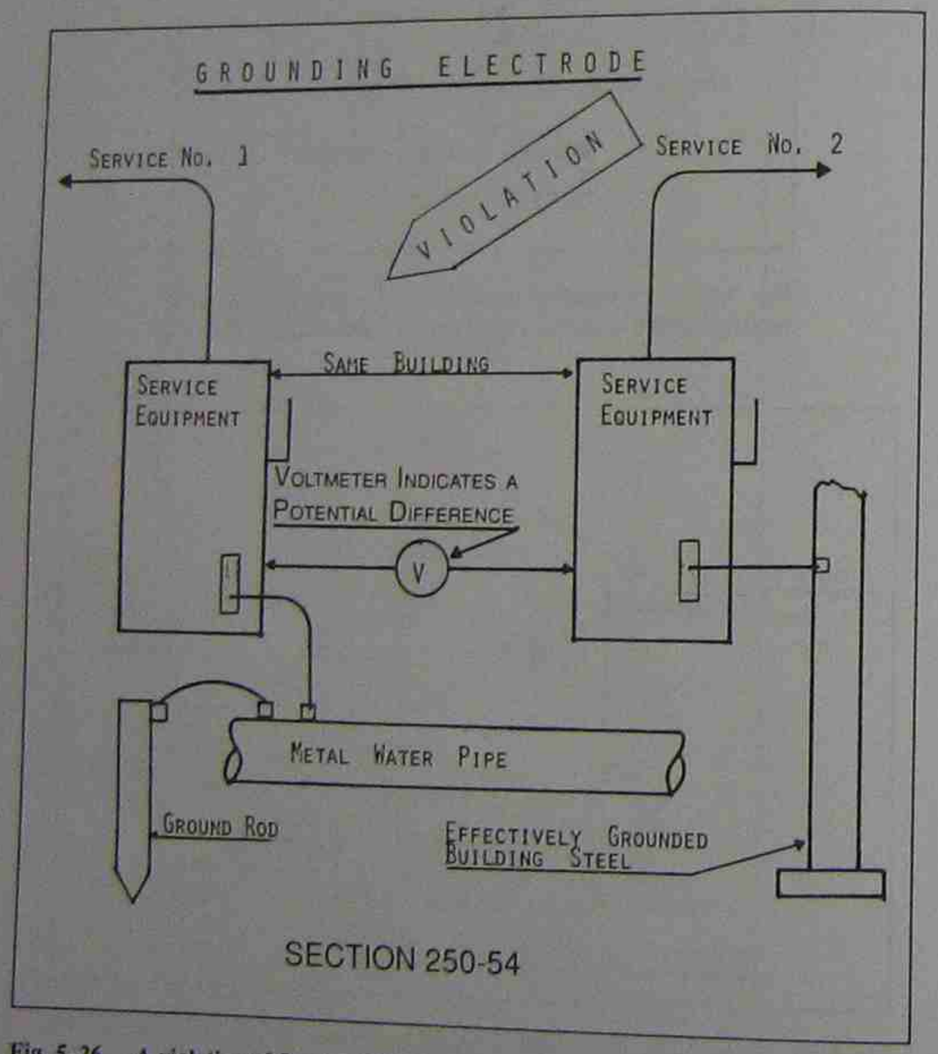


Fig. 5–26 A violation of *Section 250-84*, which specifies that two services to the same building must use the same grounding electrode.

Figure 5–27 illustrates two services using the same grounding electrode, as required by *Section 250-54*.

Figure 5–28 illustrates the use of a metal water pipe and a ground rod for one grounding electrode system and the building steel for the second service and second grounding electrode. When the two grounding electrodes are effectively bonded together, they are considered as one grounding electrode system.

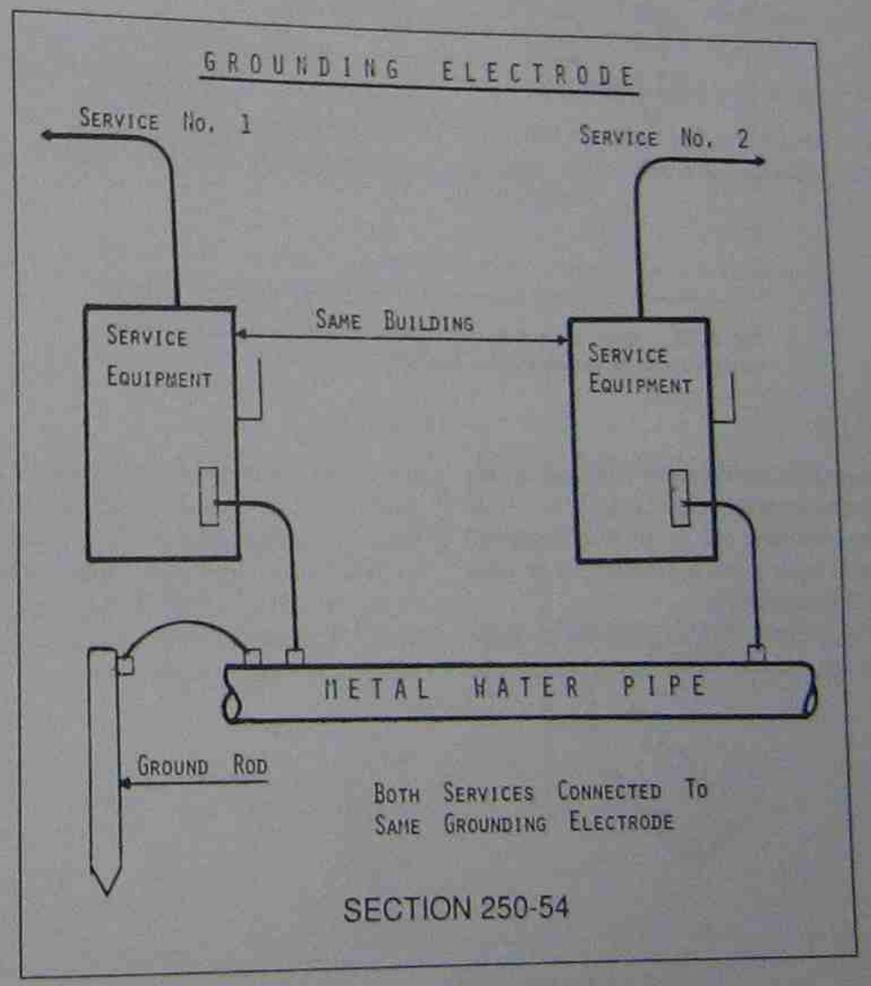


Fig. 5–27 Two services to one building using the same grounding electrode system.

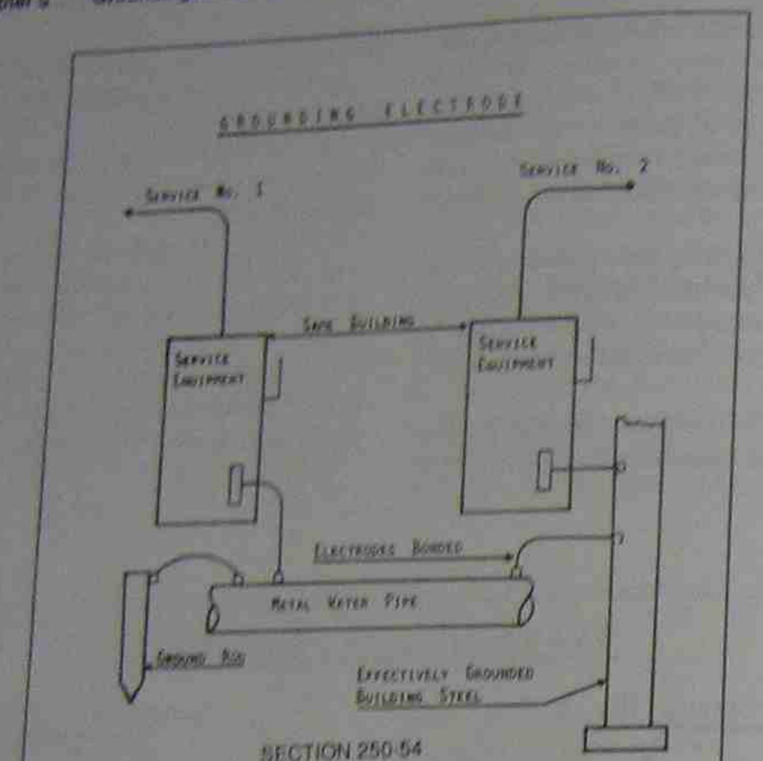


Fig. 5–28 Two services to one building using the same grounding electrode system and also connected to building steel.

SUMMARY

The grounding electrode is discussed first in this text because it is the vital point for all the grounding. Without the grounding electrode, there would be no place to connect the grounding electrode conductor.

Without the grounding electrode, there would be no place to connect the grounded conductor. Without the grounding electrode, there would be no place to connect the equipment grounding conductor. The grounding electrode is the drainpipe to earth from the bull's eye of the grounding target. The grounding electrode is the planned connection to earth to help the electrons enter the earth.

CHAPTER 6

Grounding Electrode Conductor

This chapter focuses on the grounding electrode conductor (figure 6–1). Covered are its use, materials permitted, installations, protection, and sizing.

DEFINITION OF GROUNDING ELECTRODE CONDUCTOR

The main points of the definition for the grounding electrode conductor are illustrated in figure 6–2.

1. The grounding electrode conductor will connected to:

   The equipment grounding conductor.

   The grounded conductor when a grounded system is used.

   Both when both are present.

2. It will be connected at the service equipment, at the source for separately derived systems.

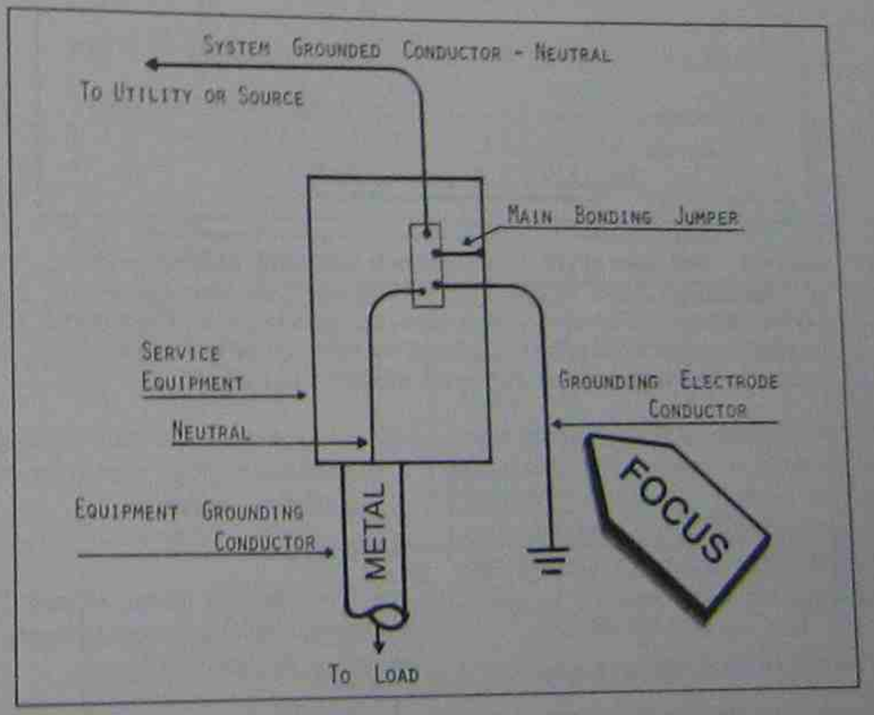


Fig. 6–1 Focus on the grounding electrode conductor.

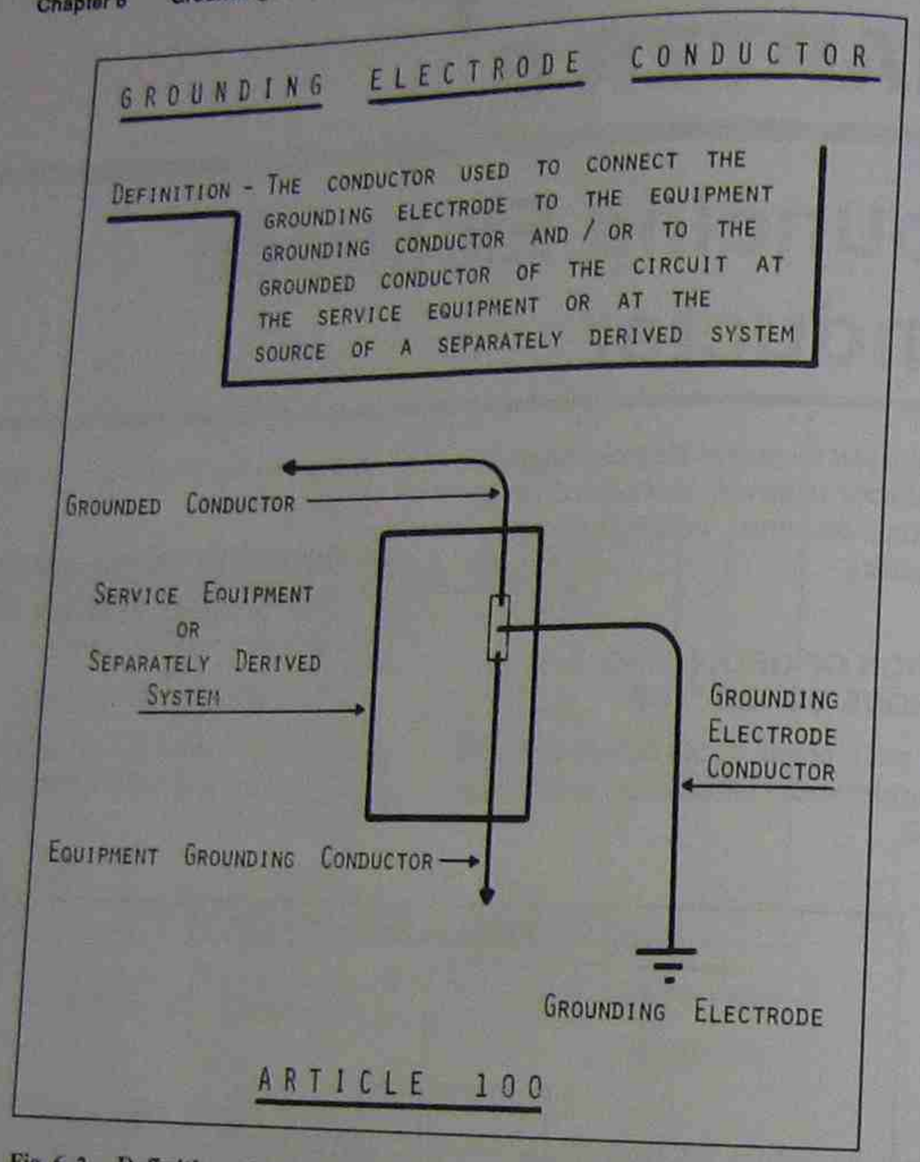


Fig. 6–2 Definition of grounding electrode conductor. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright © 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

The main purpose of the grounding electrode conductor is to connect the grounding electrode with the bull's eye of the grounding target. The grounding electrode conductor actually completes three grounding paths to the grounding electrode. These are:

1. The path from the grounded conductor
2. The path from the equipment grounding conductor when a wire is used as the equipment grounding conductor
3. The path from the main bonding jumper when raceways are used as the equipment grounding conductor

MATERIALS

When broken down, *Section 250-91(a)* shows the following requirements for the grounding electrode conductor:

1. Material
   a. Copper
   c. Copper-clad aluminum
2. Material shall
   a. Resist corrosive conditions or
   b. Be protected from corrosion
3. Solid or stranded
4. Insulated, covered, or bare
5. Continuous length with no splices (two exceptions)

Splicing

Figure 6–3 illustrates one exception for splicing the grounding electrode conductor. Splicing is allowed when a bus bar is used for the grounding electrode conductor.

Figure 6–4 illustrates Exception No. 2, which permits the grounding electrode conductor to be spliced. Three things need to be noted here. These are:

1. The grounding electrode conductor is sized according to the size of the service-entrance conductors.
2. The taps off the grounding electrode conductor are sized according to the size of the service feeder taps.
3. The tap must be carried inside the enclosure and is not connected to the outside of the enclosure.

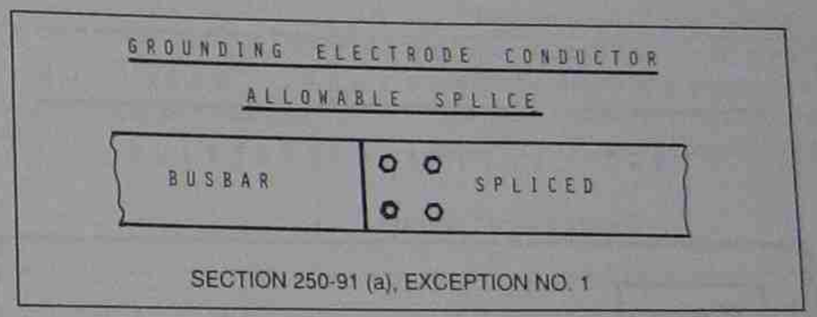


Fig. 6–3 Splicing the grounding electrode conductor using a bus bar.

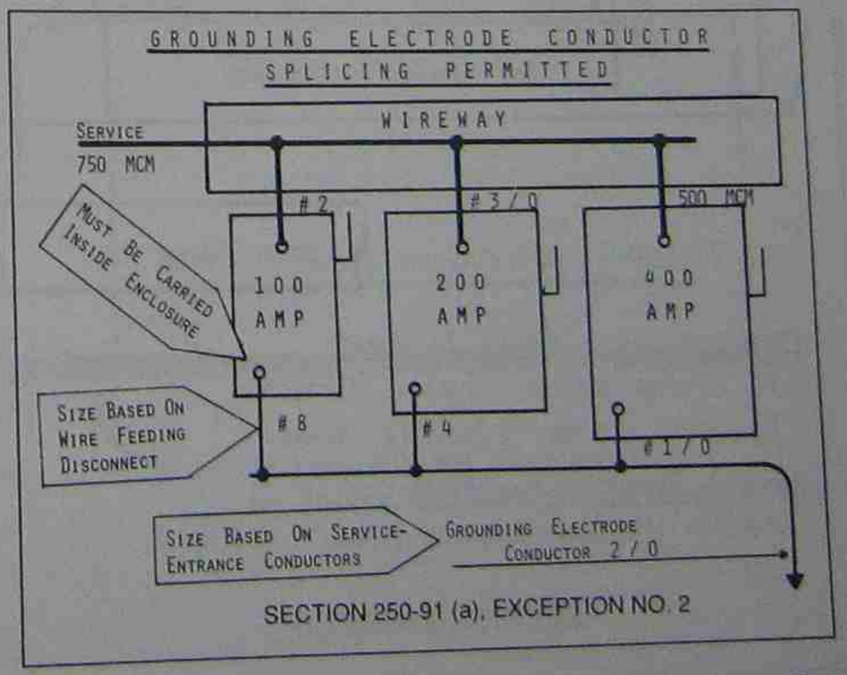


Fig. 6–4 Splicing the grounding electrode conductor when there is more than

INSTALLATION AND PROTECTION

Figure 6–5 illustrates the following items covered in *Section 250-92(a)*. In this particular section, the term *grounding conductor* means the grounding electrode conductor.

1. The grounding electrode conductor, when installed without an enclosure, shall be securely fastened to the construction surface on which it is carried.
2. The enclosure for a grounding electrode conductor shall be securely fastened to the surface on which it is carried.
3. A No. 4 copper or aluminum or larger conductor shall be protected if exposed to severe physical damage.
4. A No. 6 grounding electrode conductor that is free from exposure to physical damage shall be permitted to be run along the surface of the building construction without metal covering or protection where it is securely fastened to the construction.
5. Raceways permitted for use to protect the grounding electrode conductor include the following:

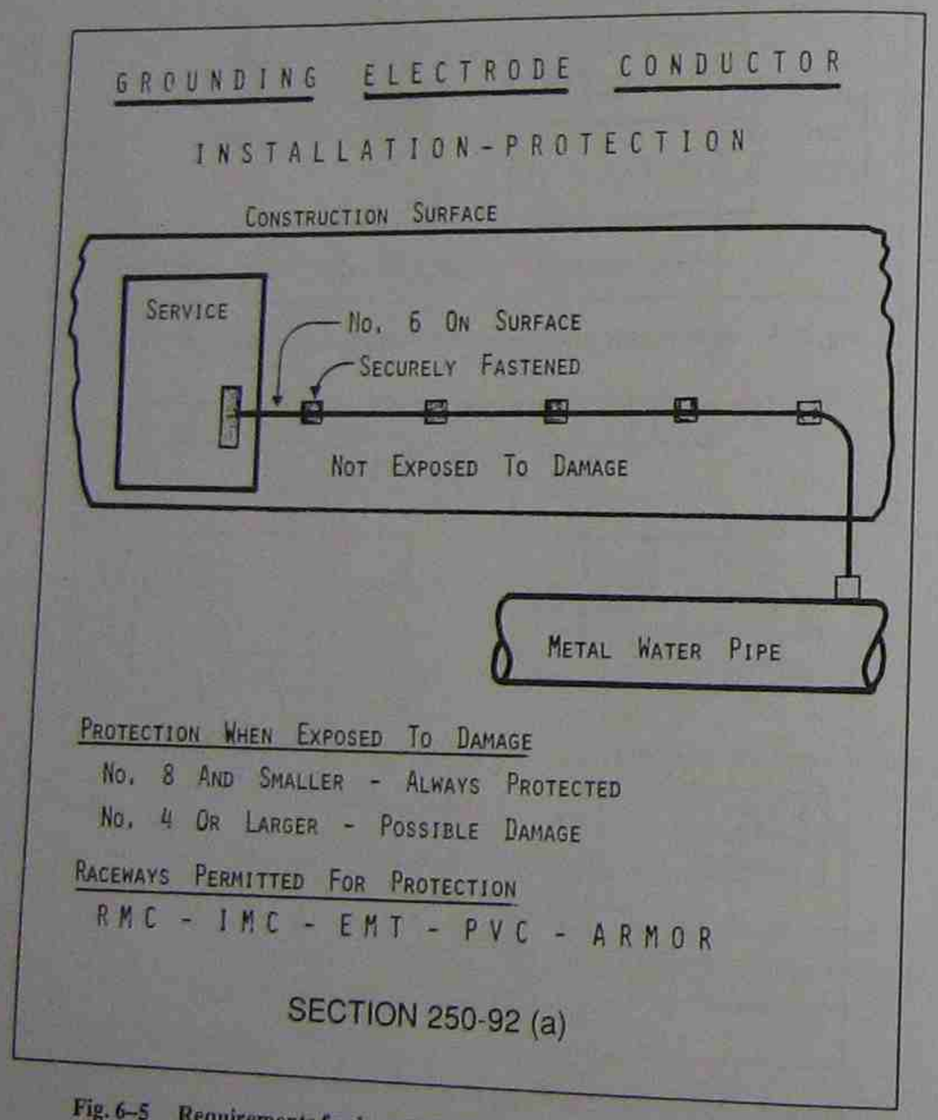


Fig. 6–5 Requirements for installing the grounding electrode conductor.

   a. Rigid metal conduit (RMC)
   b. Intermediate metal conduit (IMC)
   c. Rigid nonmetallic conduit (PVC)
   d. Electrical metallic tubing (EMT)
   e. Cable armor.
6. A grounding electrode conductor smaller than No. 6 shall be protected by one of the raceways permitted for the protection of the grounding electrode conductor.

When aluminum or copper-clad aluminum is used for the grounding electrode conductor, the following restrictions are placed on it (figure 6–6):

1. Shall not be used where in direct contact with masonry
2. Shall not be used where in direct contact with earth
3. Shall not be used where subjected to corrosive conditions
4. Where installed outside, shall not be within 18 inches of the earth.

Comment: The restrictions placed on aluminum and the copper-clad aluminum are part of the reason copper is usually specified for use as the grounding electrode conductor. The 18-inches-to-earth limitation eliminates using the aluminum or copper-clad aluminum as the grounding electrode conductor when the connection to the ground rod is either underground or less than 18 inches to earth.

Protection from a Magnetic Field

The protection of the grounding electrode conductor from destruction by a very powerful magnetic field is covered in *Section 250-92 (b)*. When metal enclosures are used for mechanical protection of the grounding electrode

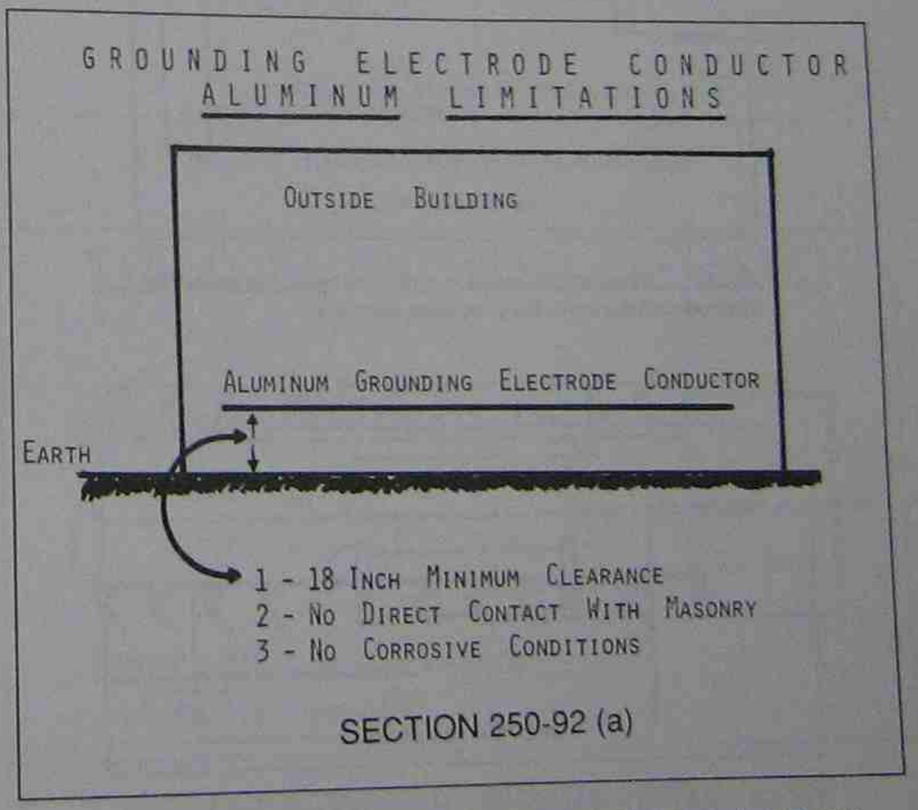


Fig. 6–6 Restrictions for using aluminum as the grounding electrode conductor.

conductor, special precautions must be taken. These are set down in *Section 250-92 (b)*.

1. The metal enclosure shall be electrically continuous from cabinets or equipment to the grounding electrode (figure 6–7).
2. The enclosure must be fastened securely to the ground clamp or fitting (figure 6–7).
3. Where the grounding electrode conductor is not protected the full length of the conductor and only for a small portion of it, both ends of the metal enclosure shall be bonded to the grounding electrode conductor.

All raceways used for protection of the grounding electrode conductor shall be installed considering the regulations set down in *Chapter 3, Wiring Methods and Materials*.

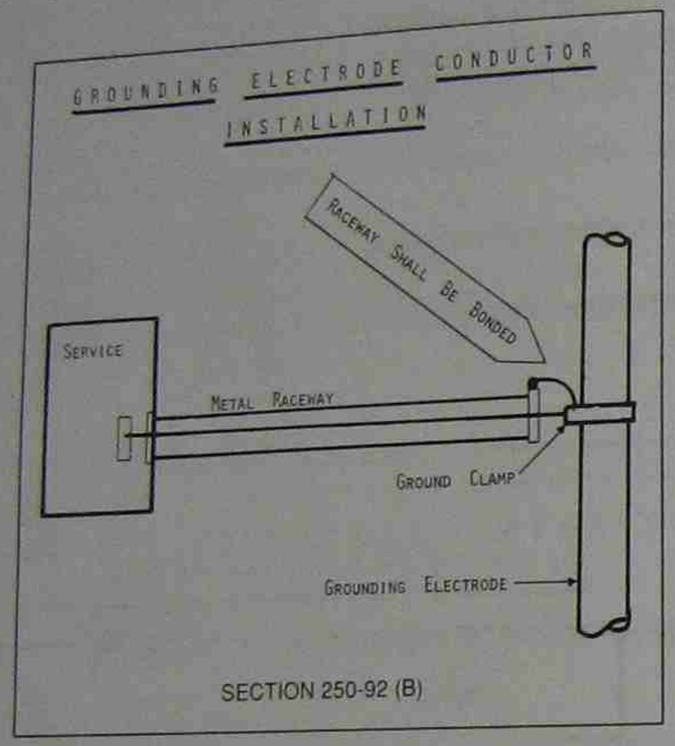


Fig. 6–7 Bonding the metal raceway enclosing the grounding electrode conductor to the grounding electrode.

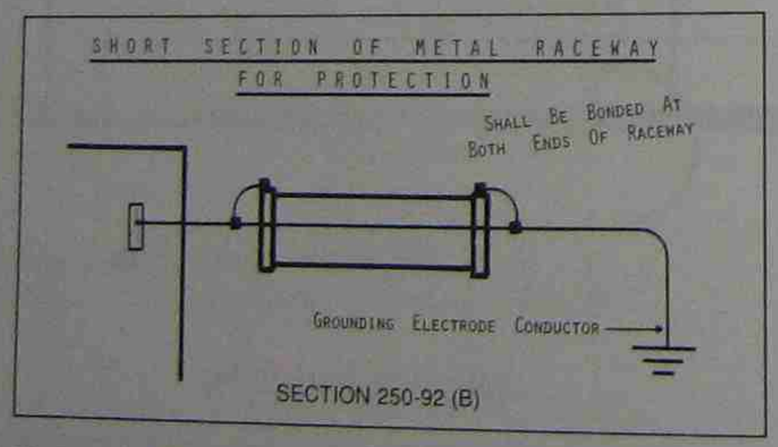


Fig. 6–8 Bonding both ends of short sections of a metal enclosure to the grounding electrode conductor.

Figures 6–7 and 6–8 illustrate two very-often-overlooked Code regulations. Ignoring these regulations can result in severe damage to the grounding electrode conductor if a fault occurs.

When an electrical conductor carries current, it sets up a magnetic field around the conductor. In the case of alternating current, it is an alternating magnetic field.

Figure 6–9 illustrates a hot conductor and a neutral conductor installed in the same metal raceway. Because the current is traveling in two different directions within the metal raceway, there is no induction in the metal raceway. The magnetic fields of the two currents flowing in opposite directions will cancel each other out.

When only one hot conductor or the neutral conductor (figure 6–10) is installed in a metal raceway, there will be induction in the metal raceway and the metal raceway will become

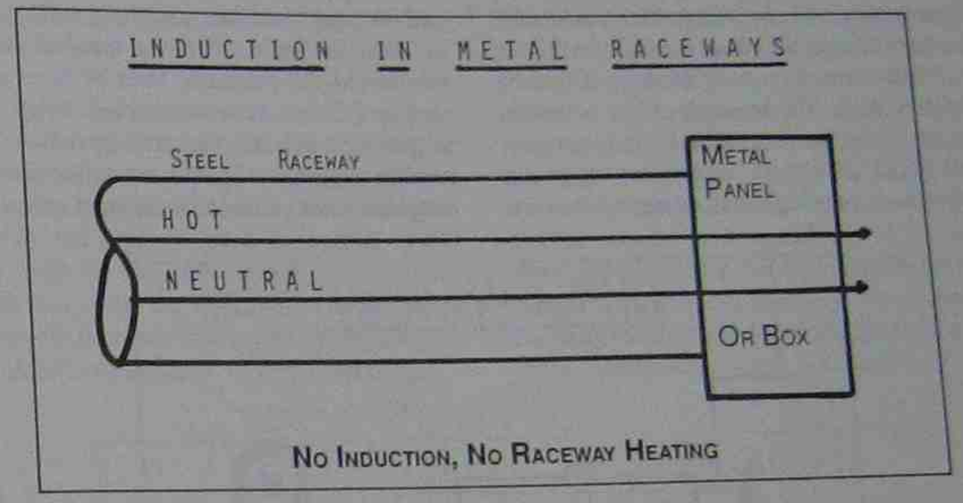


Fig. 6–9 Eliminating induction in metal raceways.

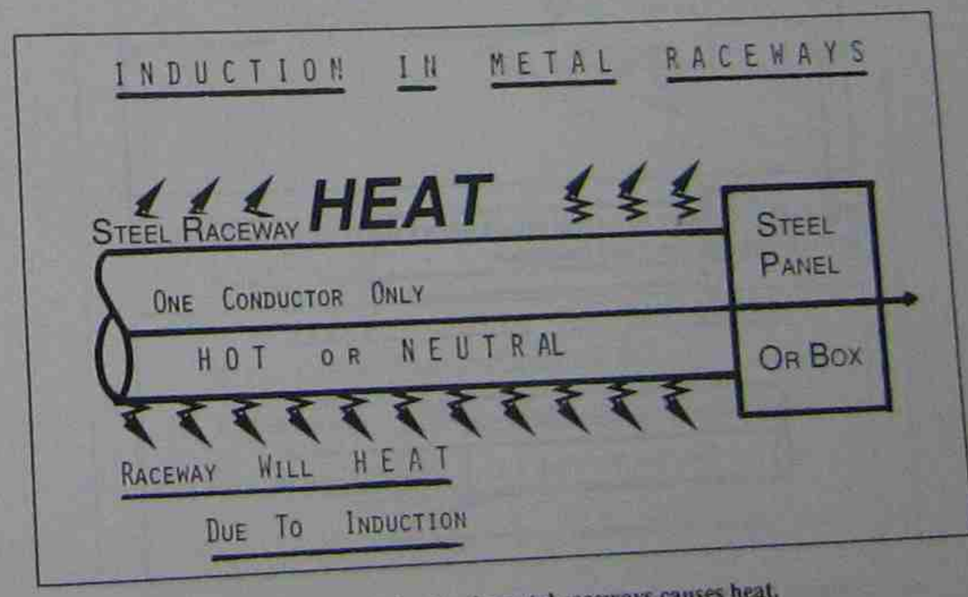


Fig. 6–10 Induction in metal raceways causes heat.

hot. The induction is due to the rise and fall of the alternating current's magnetic field.

The grounding electrode conductor for an alternating-current system is the only single alternating-current conductor that is run in a metal raceway. When only a short piece of metal raceway is used to protect the grounding electrode conductor, it must be bonded to the conductor, as shown in figure 6–8, or there will be severe heating of the metal enclosure.

Figure 6–11 illustrates an installation without the required bonding jumpers. It also indicates some of the things that could take place should a ground fault occur.

When there is a fault current, it can be extremely high. The strength of the magnetic field set up by the current is directly proportional to the amount of current flowing in the conductor. A very high fault current will cause a very intense magnetic field in a very short period of time and the conduit enclosing the grounding electrode conductor will become extremely hot. The number of lines of force that are trying to flow in the steel raceway of the grounding electrode conductor enclosure far surpass the "saturation point" of the steel raceway. *Saturation point* means the number of lines of force a piece of steel can conduct, for its cross-sectional area, without dangerous overheating.

Magnetic lines of force like to flow in steel and will search out the steel for a path to travel on. Past the point where the steel raceway is terminated, the magnetic lines of force generated by the current in the conductor will all try to get back into the nearest edge of the steel conduit (figure 6–12). The saturation point for magnetic lines of force in the steel raceway is

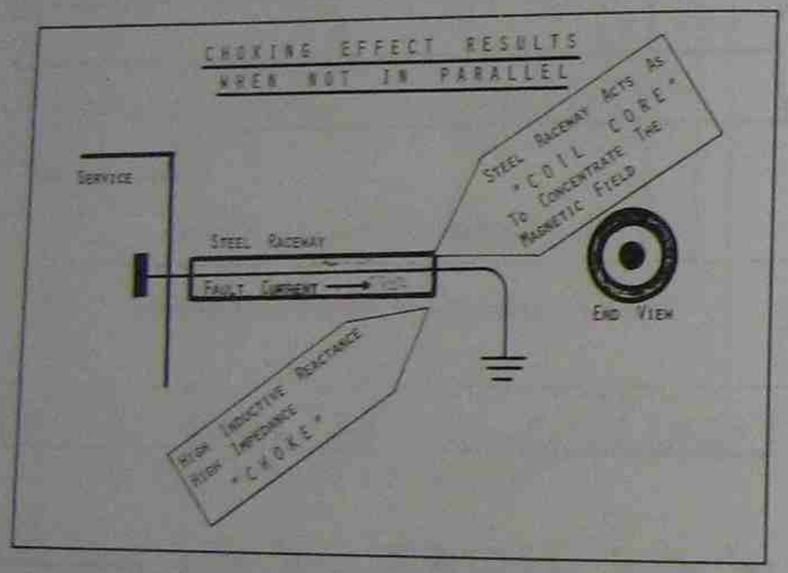


Fig. 6–11 Choking effect that occurs when a steel raceway is not bonded to the grounding electrode conductor.

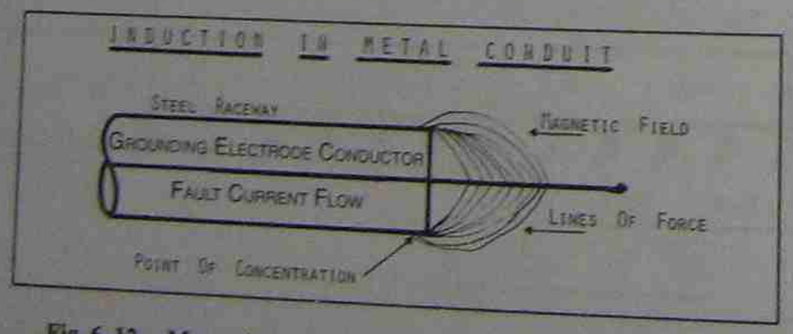


Fig. 6–12 Magnetic field at the termination of the steel raceway.

very much exceeded. Tremendous heat is generated at the point where the raceway is terminated.

The steel conduit acts like the steel core of a coil to concentrate the magnetic lines of force. It creates a high-impedance choke. Faults that have occurred when this happens have been known to melt the grounding electrode conductor in two as smoothly as if it had been cut with a knife. This occurs at the point where the steel conduit is terminated. To avoid this situation, the Code is really saying to connect the conduit enclosing the grounding electrode conductor in parallel with the grounding electrode conductor.

Figure 6–13 illustrates an experiment conducted to show the relationship between the current flow in the conductor and the current flow in the conduit surrounding the conductor. A controlled supply is used that furnishes 100 amps, with the conductor and the conduit connected in parallel and an ammeter connected in series with both the conductor and the conduit. The result, as indicated, is very surprising.

When two service or feeder conductors are connected in parallel, they are expected to act as one conductor. In this case the conduit and the copper conductor act as one conductor. The current also looks at it as one conductor, which gives rise to the question, Why does so much more current flow in the steel conduit than in the copper wire conductor?

The answer is, Because of the "skin effect." The *skin effect* is the tendency for the current to flow on the outer edge of the conductor. Aluminum is a nonmagnetic material. PVC (nonmetallic conduit) is a nonmagnetic material. The magnetic-field problem does not exist when the grounding electrode conductor is installed in rigid nonmetallic conduit or aluminum conduit or aluminum electrical metallic tubing. Induction, as illustrated in figure 6–10, will take place in an aluminum raceway when only one conductor is installed in it. However, when the grounding electrode conductor is installed in aluminum raceway, the aluminum raceway must be bonded to the grounding electrode conductor. When nonmetallic PVC is

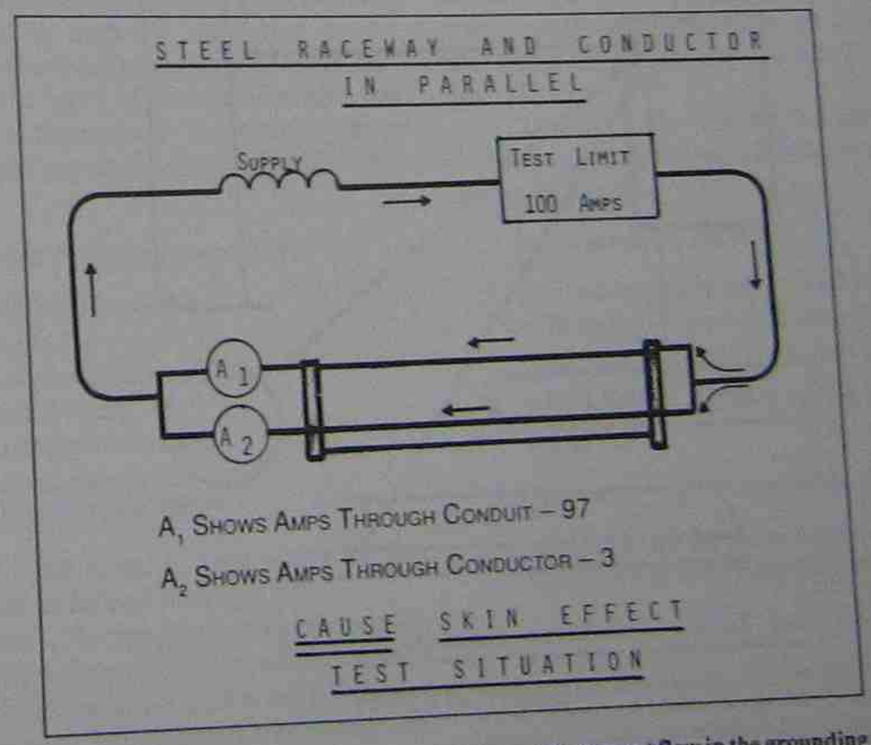


Fig. 6–13 Test showing the relationship between the current flow in the grounding electrode conductor and the metal conduit enclosure when they are bonded together.

used, there is no induction, no need for bonding. It is not required.

CONNECTING THE GROUNDING ELECTRODE CONDUCTOR

Section 250-81 requires an unspliced grounding electrode conductor to be installed and permits it to be installed to any convenient grounding electrode of the grounding electrode system (figure 6–14). *Section 250-112*, with its exceptions, lists the required accessible connections for the grounding electrode conductor. These are illustrated in figure 6–15. The basic rule for connecting the grounding electrode conductor to the grounding electrode is given in *Section 250-112*, with special emphasis on these points:

1. The connection shall be accessible.
2. The connection shall be made to assure a permanent and effective ground.

The exception to this section allows for some plain common sense. It states that when a buried electrode is used, the connection between the grounding electrode conductor and the grounding electrode need not be accessible, such as in the case of the following:

1. Concrete-encased grounding electrode
2. Driven grounding electrode
3. Buried grounding electrode

Comment: About the only electrode left that is required to be accessible is the metal water pipe and building steel.

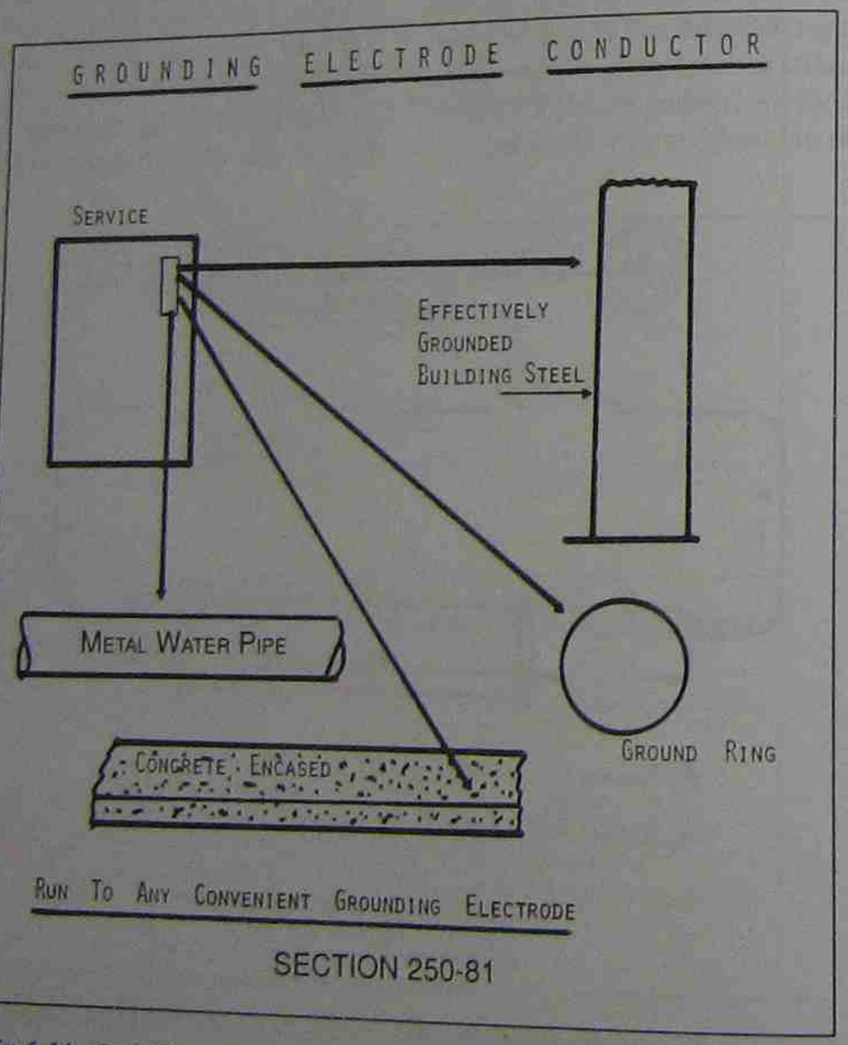


Fig. 6–14 Installing a grounding electrode conductor to a grounding electrode.

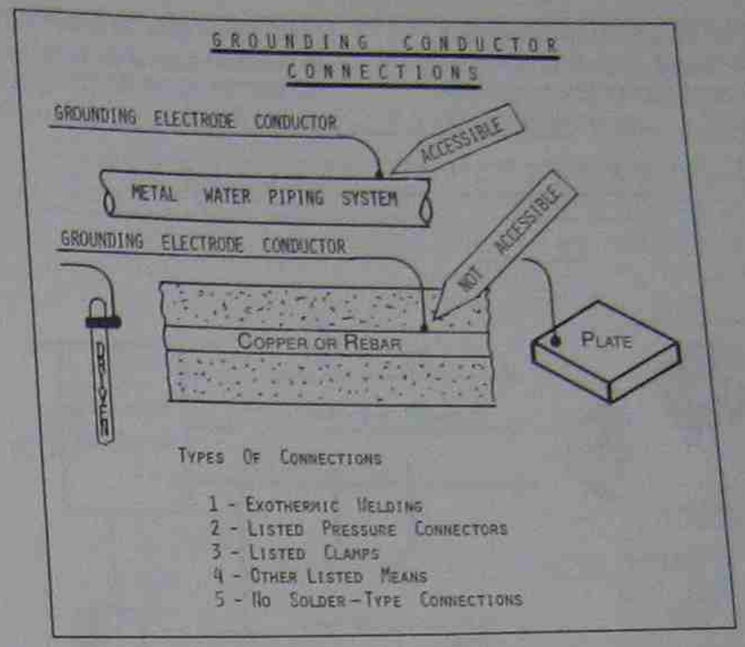


Fig. 6–15 Types and location of connections for the grounding electrode conductor to a grounding electrode.

The materials and methods for connecting the grounding electrode conductor to the grounding electrode are outlined in *Section 250-115*. Various types of these connections are illustrated in figure 6–16. The following is an outline of the important points of *Section 250-115*:

1. Methods of making connections
   a. Exothermic welding
   b. Listed lug
   c. Listed pressure connector
   d. Listed clamp
   e. Listed bolted clamp
   f. Listed sheet metal strap
   g. Other listed means

The word *listed* is very visible in this section and is defined in *Article 100*.

Quote – "Listed: Equipment or materials included in a list published by an organization acceptable to the authority having jurisdiction and concerned with product evaluation, that maintains periodic inspection of production of listed equipment or materials, and whose listing states either that the equipment or material meets appropriate standards or has been tested and found suitable for use in a specified manner."*

Comment: The means for identifying listed equipment may vary. It may be listed and it may be labeled.

2. No dependency on solder
3. Ground clamps to be material compatible with material they will clamp to; no aluminum ground clamps on copper piping
4. Where buried, connection listed for direct burial
5. Not more than one conductor per clamp
6. Clamps listed for more than one conductor permitted to have more than one conductor

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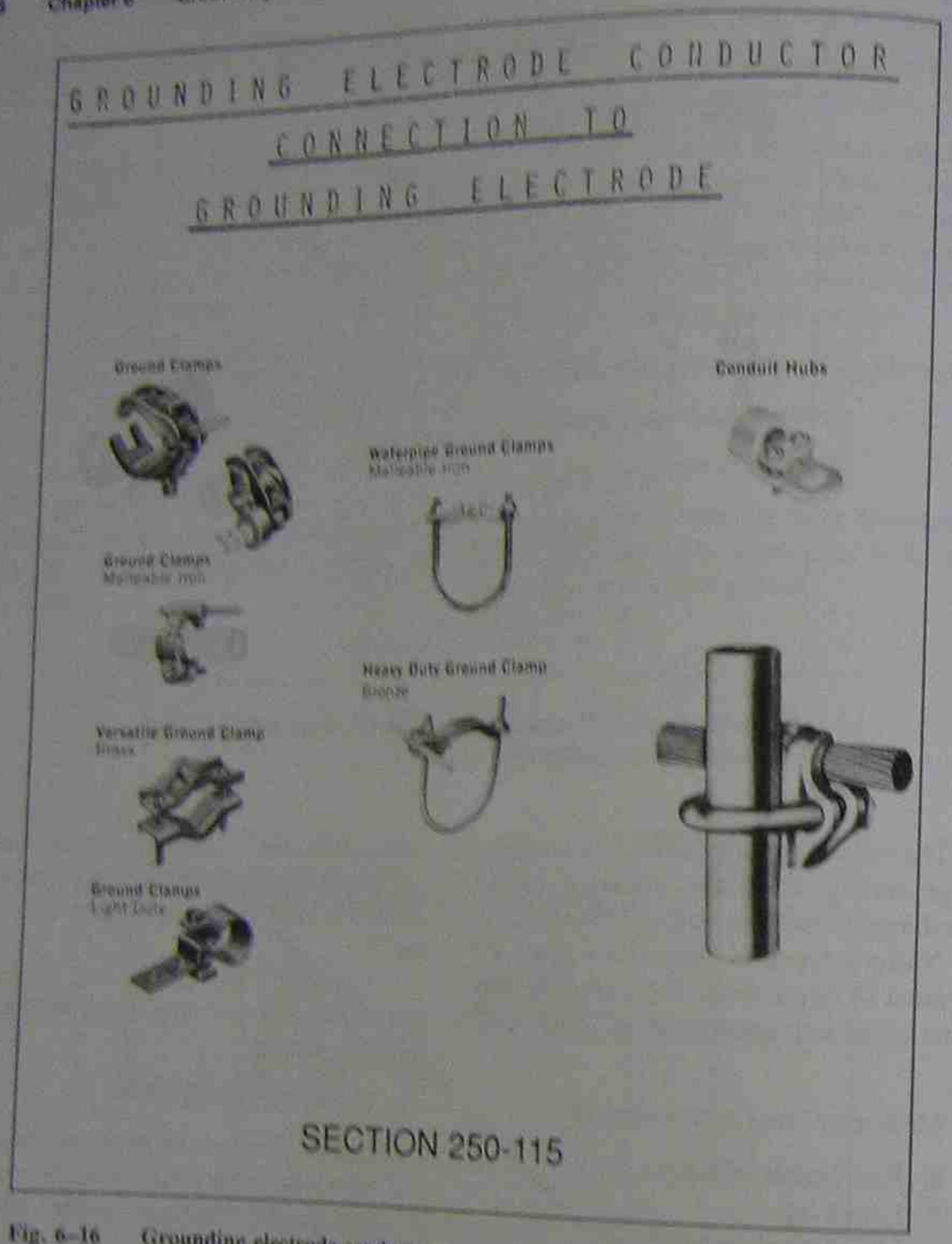

Fig. 6–16 Grounding electrode conductor connections to the grounding electrode. Photo courtesy Thomas & Betts Corporation.

7. Listed bolted clamps permitted: cast bronze, brass, plain iron, or malleable iron
8. Devices that screw into pipe: an approved or listed plug or fitting
9. Listed sheet-metal straps limitations
   a. Rigid metal base
   b. Seats on electrode
   c. Not liable to stretch during installation or with time
10. An equally substantial approved means substituted for any of the above.

SIZING THE DC GROUNDING ELECTRODE CONDUCTOR

There are three ways of sizing the direct-current grounding electrode

1. Three-wire balancer set, with overcurrent protection in case of unbalanced condition. The grounding electrode shall not be smaller than neutral (figure 6–17).
2. DC systems other than the three-wire balancer. The grounding electrode conductor shall not be smaller than the largest conductor (figure 6–18).

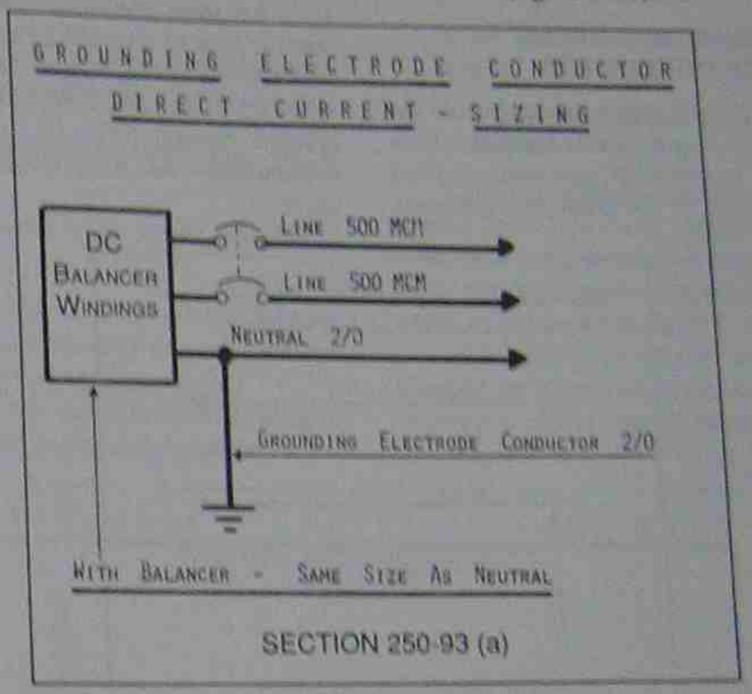

Fig. 6–17 Sizing a grounding electrode conductor for a DC system with balancer windings.

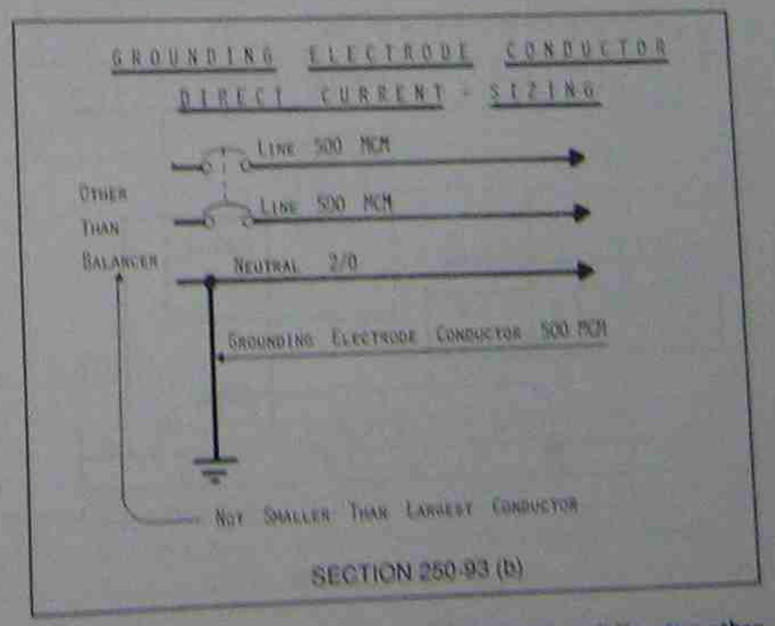

Fig. 6–18 Sizing a grounding electrode conductor for a DC system other

3. In no case shall the grounding conductor be smaller than No. 8 copper or No. 6 aluminum (figure 6–19).

SIZING THE AC GROUNDING ELECTRODE CONDUCTOR

Section 250-94 states the basic rule for sizing the grounding electrode conductor for a grounded or ungrounded alternating-current system. "The size of the grounding electrode conductor of a grounded or ungrounded AC system shall not be less than that given in *Table 250-94*" (figure 6–20).

There are two exceptions to the basic rule. Each has three parts to it and is directed at a specific type of grounding electrode.

Exception No. 1 applies to grounded systems. Exception No. 2 applies to ungrounded systems. Exception No. 1a. lists the following requirements for a *grounded system* (figure 6–21):

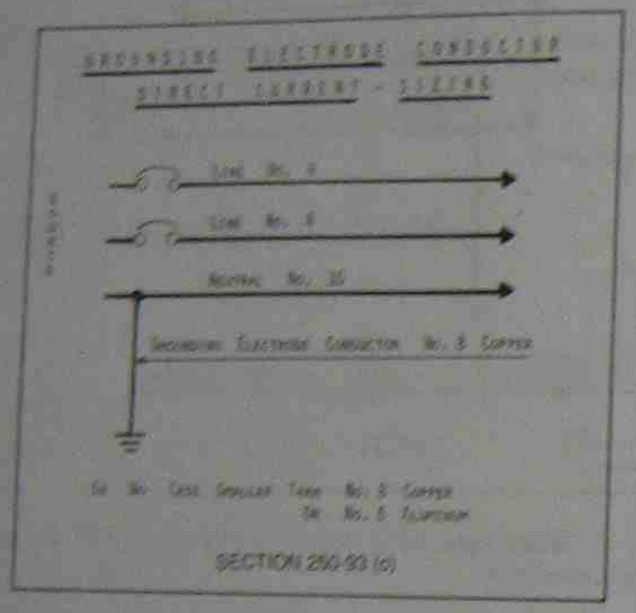

Fig. 6–19 The minimum size of a grounding electrode conductor permitted for a DC system.

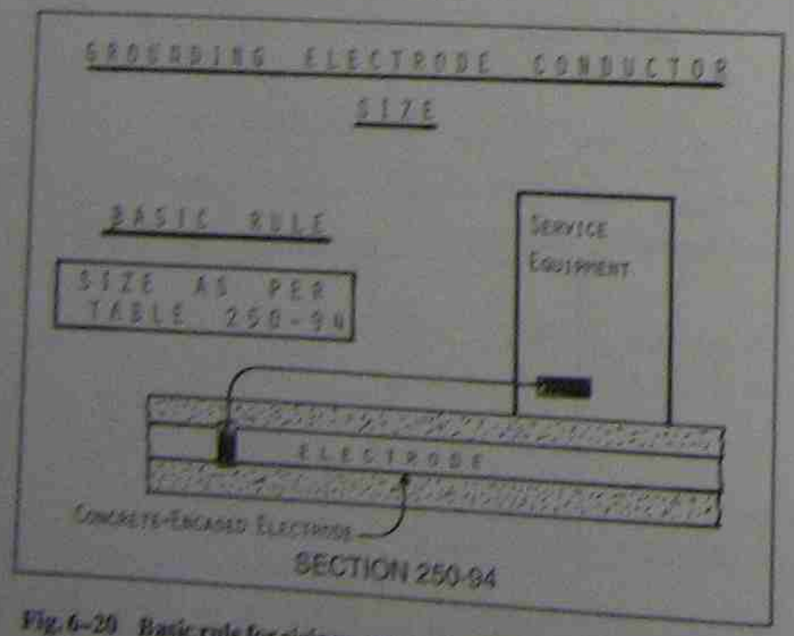

Fig. 6–20 Basic rule for sizing a grounding electrode conductor for an AC system.

1. Applies to made electrodes only, such as rod, pipe, or plate electrodes
2. Requires a sole connection between the grounding electrode and the grounded conductor of the grounded system

Comment: Sole connection means there are no bonding jumpers in the circuit.

3. Is not required to be larger than No. 6 copper
4. Is not required to be larger than No. 4 aluminum

Exception No. 2, *Ungrounded Systems*, parallels the requirements for grounded systems in each of its four parts (figure 6–22).

Exception No. 2a. lists the following requirements for an *ungrounded system*:

1. Applies to made electrodes, such as rod, pipe, or plate electrodes
2. Requires a sole connection between the grounding electrode and service
3. Is not required to be larger than No. 6 copper
4. Is not required to be larger than No. 4 aluminum

The smaller conductor is also permitted by *Section 250-81 (a)*, last paragraph, when the water pipe is the primary electrode and is supplemented by a ground rod, pipe, or plate electrode, as illustrated in figure 6–23.

Question: Why is this small conductor allowed for a grounding electrode conductor, regardless of the size of the service-entrance conductors?

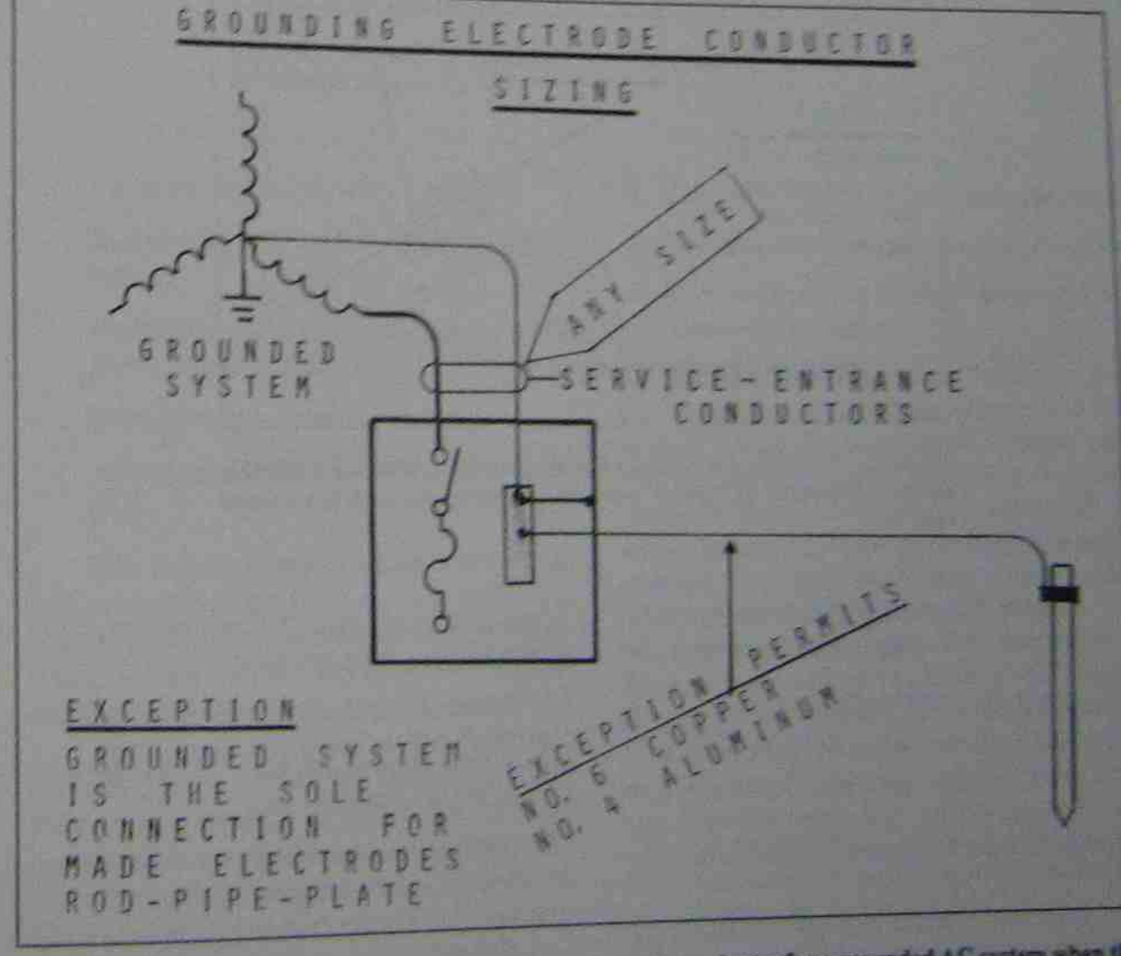

Fig. 6–21 Exception permitting a smaller grounding electrode conductor for a grounded AC system when the grounding electrode is a ground rod.

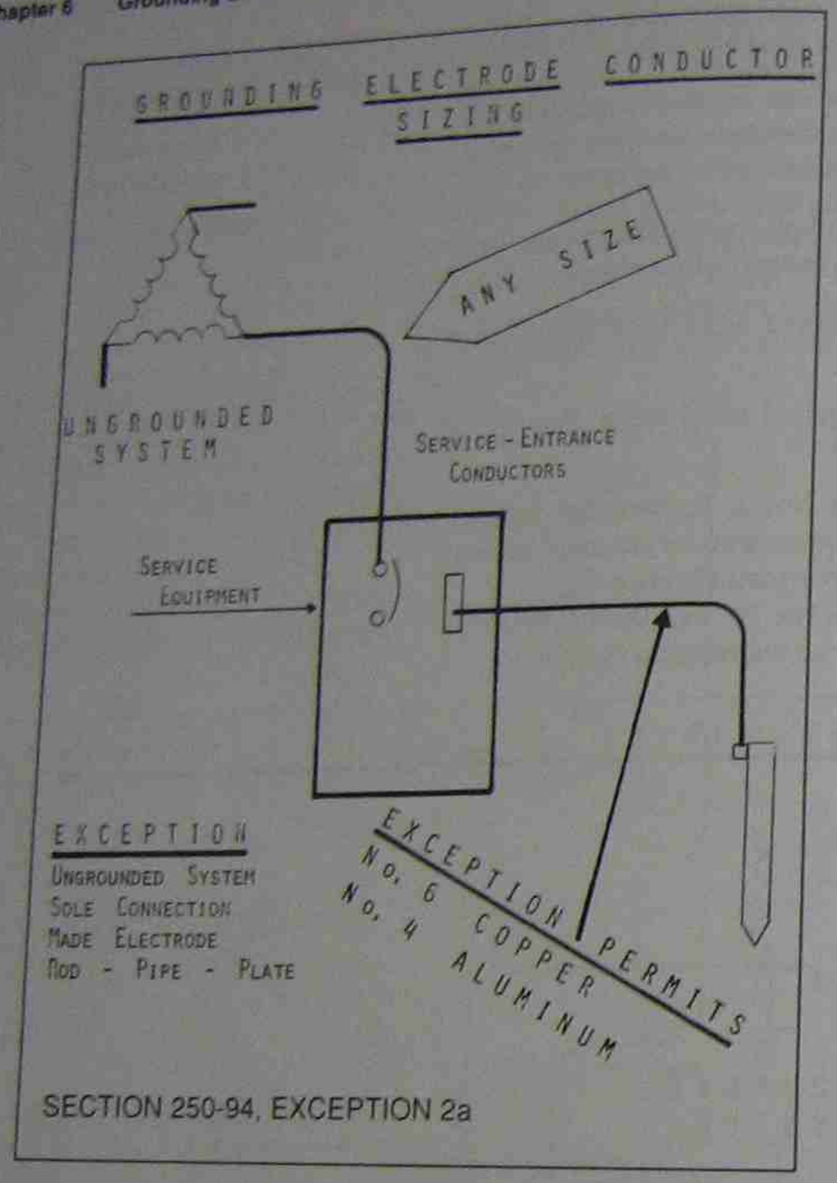

Fig. 6–22 Exception permitting a smaller grounding electrode conductor for an ungrounded AC system when the grounding electrode is a ground rod.

Answer: Because the No. 6 copper or No. aluminum will carry all the electrons the rounding electrode can dissipate into the earth the given time limit. The grounding electrode the limiting factor. When a larger conductor is ed, the grounding electrode chokes down on e electron traffic and they all can't get rough, so there is no need for a larger conduc-

Technical reports indicate the following ngs were taken into consideration by the de-making panel responsible for *Article 250,* when first permitting the use of the small grounding electrode conductor.

1. Maximum fault current for 5 seconds
2. 1 amp allowed for each 30 circular mils (CM) of conductor area
3. Voltage drop at maximum fault current limited to 40 volts per 100 feet

Example:

No. 6 copper = 26,240 circular mils

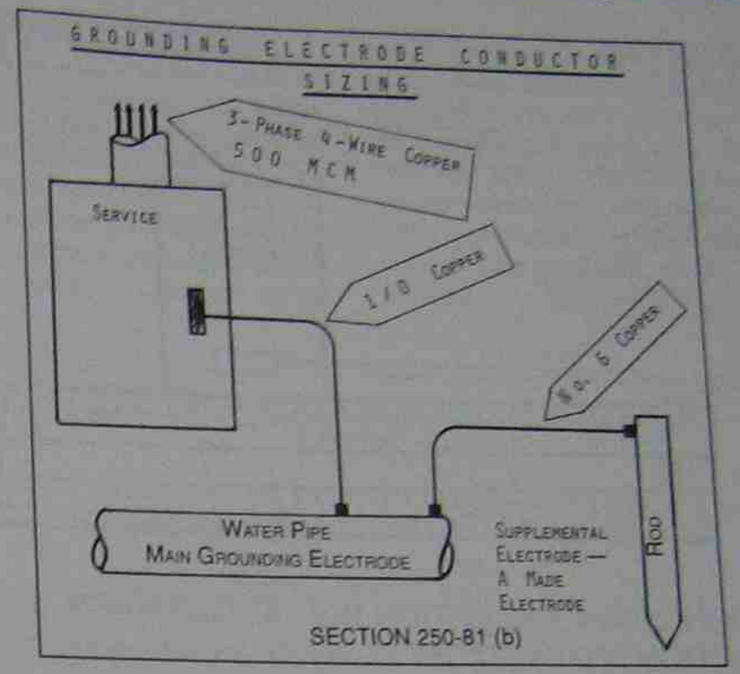

Fig. 6–23 Primary and secondary grounding electrode conductors can be different sizes.

1 amp per 30 circular mils

26,240 CM / 30 CM = 875 amps fault current

Resistance of No. 6 = .0426 ohm per 1000 feet (Chapter 9, Table 8)

Voltage drop = amps x ohms

Voltage drop = 875 x .0426 = 37.3 volts drop

This indicates the No. 6 copper conductor will carry 875 amps for 5 seconds without a voltage drop of more than 40 volts per 100 feet. It is hoped the fault will be cleared or will clear itself in 5 seconds or less.

The second exception to the basic rule given in *Section 250-94*, Exception No. 1b., is for grounded systems; Exception No. 2b. is for ungrounded systems. The two exceptions parallel each other and are illustrated in figure 6–24. The following is a breakdown of the exceptions:

1. Applies only to concrete-encased electrodes
2. Sole connection to the grounding electrode
3. Not required to be larger than No. 4 copper
4. Only copper to be used for the grounding electrode conductor

The third exception to the basic rule, Exception No. 1c. for grounded systems and Exception No. 2c. for ungrounded systems, permits the use of a smaller grounding electrode conductor than that required by *Table 250-94* when a ground ring-type grounding electrode is installed. The two exceptions parallel each other and are illustrated in figure 6–25.

The special parts are:

1. Applies to the ground ring-type grounding electrode only
2. Requires a sole connection
3. Not required to be larger than the ground ring conductor, which is established as No 2 copper by *Section 250-81 (d)*
4. Only copper to be used for the grounding electrode conductor

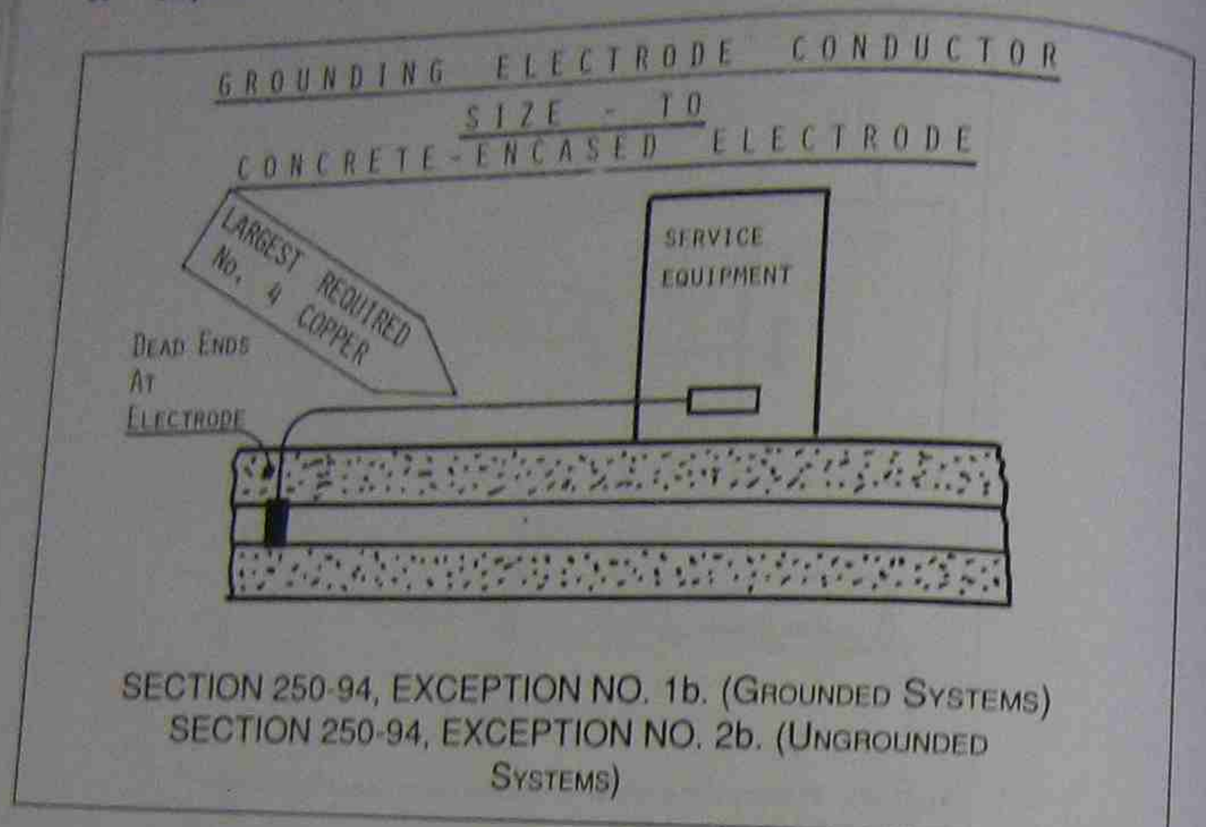

Fig. 6–24 The exception permitting a smaller grounding electrode conductor to be installed when a concrete-encased electrode is used.

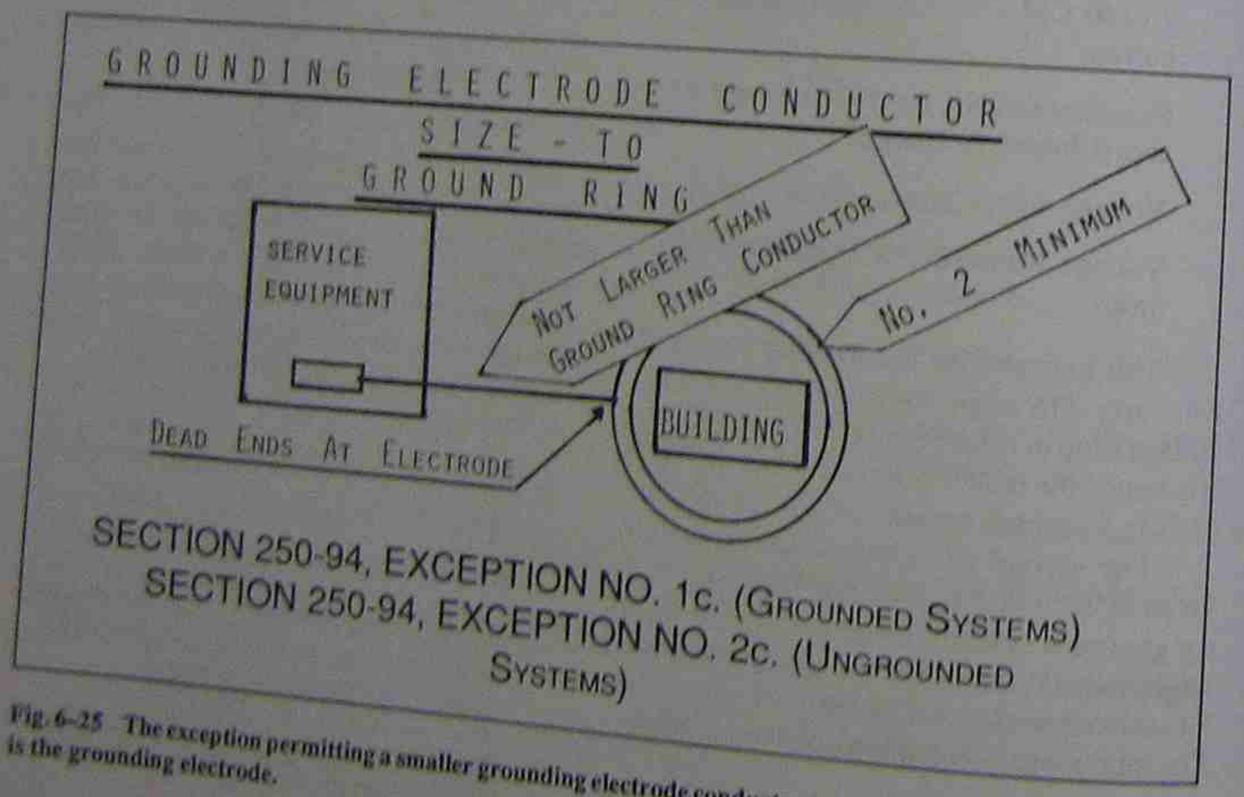

Fig. 6–25 The exception permitting a smaller grounding electrode conductor to be installed when a ground ring is the grounding electrode.

SIZING GROUNDING ELECTRODE CONDUCTORS

Figure 6–26 illustrates size 500 MCM copper used as the service-entrance conductors for a grounded system with a copper grounding electrode conductor. Therefore, the basic rule applies. The size of the grounding electrode conductor is taken directly from *Table 250-94* and is No. 1/0 copper, as illustrated in figure 6–27.

Figure 6–28 illustrates 350 MCM co as the service-entrance conductors fo grounded system, and a copper grounding trode conductor is being used. Therefore basic rule applies. The size of the groun electrode conductor is taken directly from *250-94*, as illustrated in figure 6–29; a gr ing electrode conductor of No. 2 copp required.

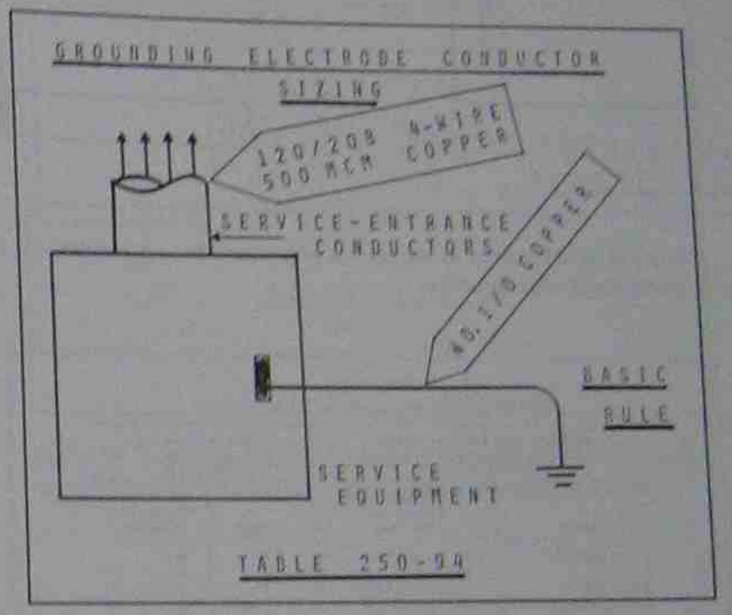

Fig. 6–26 Using 500 MCM copper as the service conductors for a grounded AC system with a copper grounding electrode conductor.

Table 250-94
Grounding Electrode Conductor for AC Systems

Size of Largest Service-Entrance Conductor or Equivalent Area for Parallel Conductors		Size of Grounding Electrode Conductor	
Copper	Aluminum or Copper-Clad Aluminum	Copper	*Aluminum or Copper-Clad Aluminum
2 or smaller	0 or smaller	8	6
1 or 0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250 MCM	4	2
Over 3/0 thru 350 MCM	Over 250 MCM thru 500 MCM	2	0
Over 350 MCM thru 600 MCM	Over 500 MCM thru 900 MCM	0	3/0
Over 600 MCM thru 1100 MCM	Over 900 MCM thru 1750 MCM	2/0	4/0
Over 1100 MCM	Over 1750 MCM	3/0	250 MCM

Fig. 6–27 Reading *Table 250-94* for sizing the grounding electrode conductor for the service illustrated in figure 6–26. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright © 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

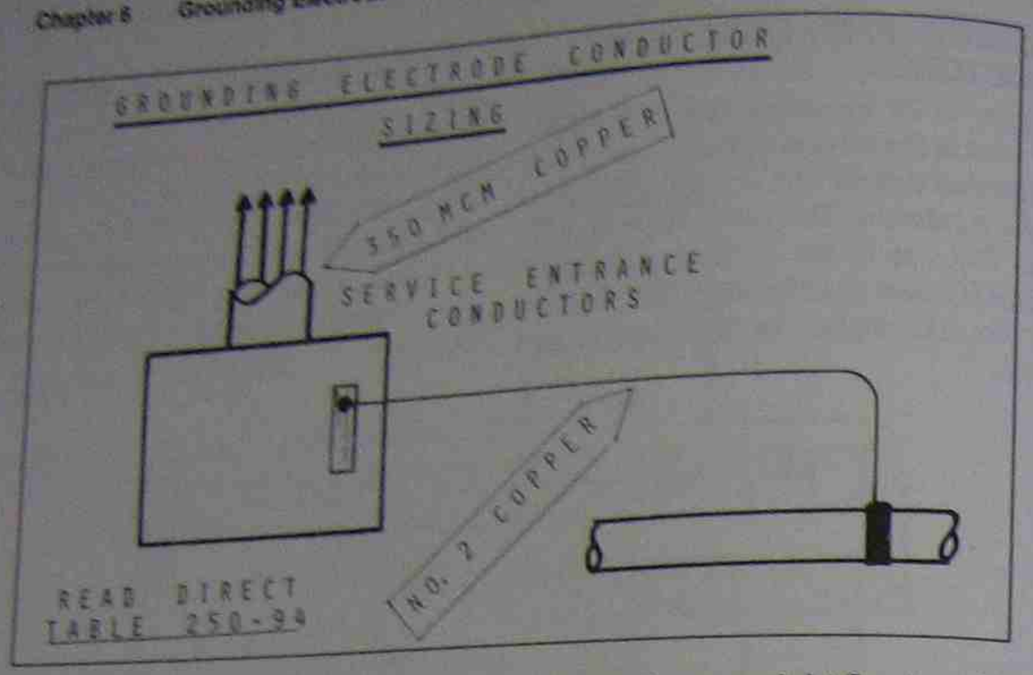

Fig. 6–28 Using 350 MCM copper as the service conductors for a grounded AC system with a copper grounding electrode conductor.

Table 250-94
Grounding Electrode Conductor for AC Systems

Size of Largest Service-Entrance Conductor or Equivalent Area for Parallel Conductors		Size of Grounding Electrode Conductor	
Copper	Aluminum or Copper-Clad Aluminum	Copper	*Aluminum or Copper-Clad Aluminum
2 or smaller	0 or smaller	8	6
1 or 0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250 MCM	4	2
Over 3/0 thru 350 MCM	Over 250 MCM thru 500 MCM	2	0
Over 350 MCM thru 600 MCM	Over 500 MCM thru 900 MCM	0	3/0
Over 600 MCM thru 1100 MCM	Over 900 MCM thru 1750 MCM	2/0	4/0
Over 1100 MCM	Over 1750 MCM	3/0	250 MCM

Fig. 6–29 Reading *Table 250-94* for sizing the grounding electrode conductor for the service illustrated in figure 6–28. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright © 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

Figure 6–30 illustrates size 4/0 aluminum ice-entrance conductors for a grounded em; an aluminum grounding electrode con- or is used. Again, the basic rule applies. The of the grounding electrode conductor is directly from *Table 250-94* and, as illus- in figure 6–31, a grounding electrode uctor of No. 2 aluminum is required.

Figure 6–32 illustrates the use of service- nce conductors in parallel for a grounded system. There are two size 4/0 copper conductors, paralleled, per phase and a copper grounding electrode conductor is used.

Table 8, Conductor Properties (figure 6–33) is used to calculate the total circular-mil area of the service-entrance conductors. Then, the basic rule applies.

4/0 = 211,600 CM x 2 conductors

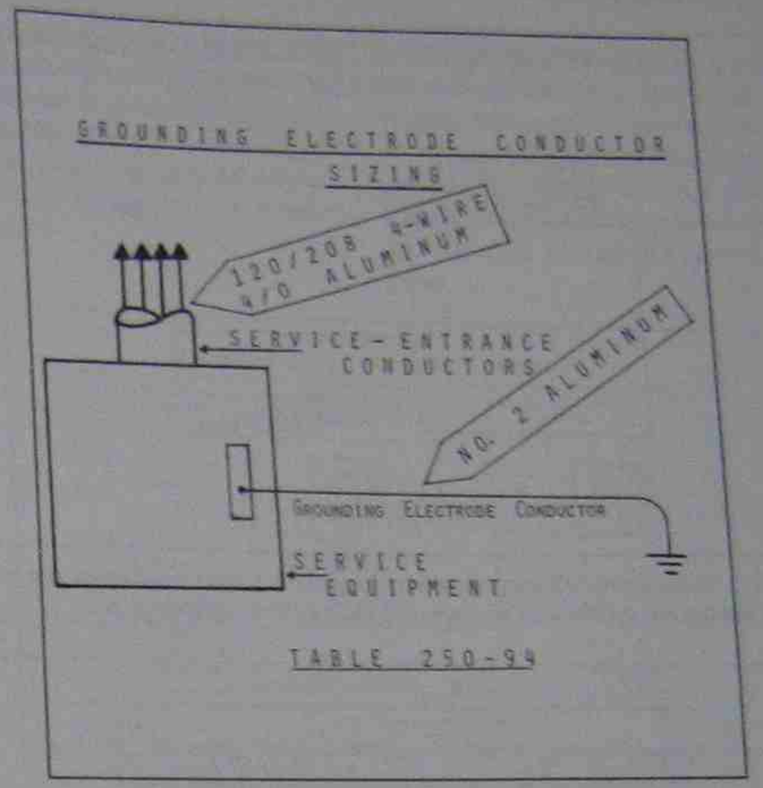

Fig. 6–30 Using No. 4/0 aluminum service conductors for a grounded AC system with an aluminum grounding electrode conductor.

Table 250-94
Grounding Electrode Conductor for AC Systems

Size of Largest Service-Entrance Conductor or Equivalent Area for Parallel Conductors		Size of Grounding Electrode Conductor	
Copper	Aluminum or Copper-Clad Aluminum	Copper	*Aluminum or Copper-Clad Aluminum
2 or smaller	0 or smaller	8	6
1 or 0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250 MCM	4	2
Over 3/0 thru 350 MCM	Over 250 MCM thru 500 MCM	2	0
Over 350 MCM thru 600 MCM	Over 500 MCM thru 900 MCM	0	3/0
Over 600 MCM thru 1100 MCM	Over 900 MCM thru 1750 MCM	2/0	4/0
Over 1100 MCM	Over 1750 MCM	3/0	250 MCM

Fig. 6–31 Reading *Table 250-94* for sizing the grounding electrode conductor for the service illustrated in figure 6–30. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright © 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

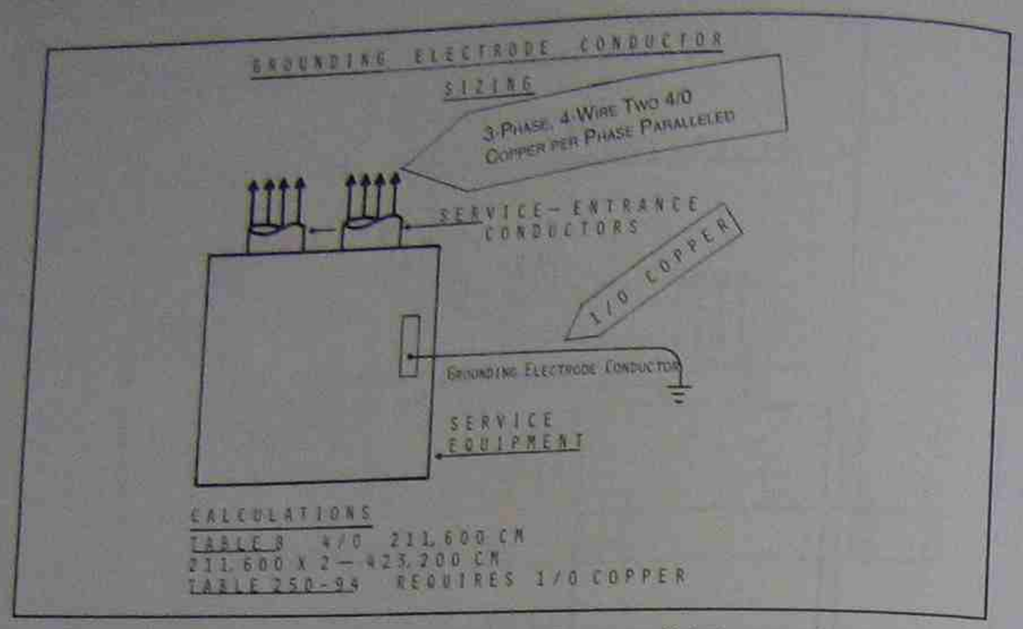

Fig. 6–32 Using two No. 4/0 copper conductors per phase, paralleled, as service conductors for a grounded AC system with a copper grounding electrode conductor.

Table 8. Conductor Properties

Size AWG/ MCM	Area Cir. Mils	DC Resistance at 75°C. 167°F Stranding Quantity	Stranding Diam. In.	Overall Diam. In.	Overall Area In.²	Copper Uncoated ohm/MFT	Copper Coated ohm/MFT	Aluminum ohm/MFT
18	1620	1	—	0.040	0.001	7.77	8.08	12.8
18	1620	7	0.015	0.046	0.002	7.95	8.45	13.1
16	2580	1	—	0.051	0.002	4.89	5.08	8.05
16	2580	7	0.019	0.058	0.003	4.99	5.29	8.21
14	4110	1	—	0.064	0.003	3.07	3.19	5.06
14	4110	7	0.024	0.073	0.004	3.14	3.26	5.17
12	6530	1	—	0.081	0.005	1.93	2.01	3.18
12	6530	7	0.030	0.092	0.006	1.98	2.05	3.25
10	10380	1	—	0.102	0.008	1.21	1.26	2.00
10	10380	7	0.038	0.116	0.011	1.24	1.29	2.04
8	16510	1	—	0.128	0.013	0.764	0.786	1.26
8	16510	7	0.049	0.146	0.017	0.778	0.809	1.28
6	26240	7	0.061	0.184	0.027	0.491	0.510	0.808
4	41740	7	0.077	0.232	0.042	0.308	0.321	0.508
3	52620	7	0.087	0.260	0.053	0.245	0.254	0.403
2	66360	7	0.097	0.292	0.067	0.194	0.201	0.319
1	83690	19	0.066	0.332	0.087	0.154	0.160	0.253
1/0	105600	19	0.074	0.373	0.109	0.122	0.127	0.201
2/0	133100	19	0.084	0.419	0.138	0.967	0.101	0.159
3/0	167800	19	0.094	0.470	0.173	0.0766	0.0797	0.126
4/0	211600	19	0.106	0.528	0.219	0.0608	0.0626	0.100
250	—	37	0.082	0.575	0.260	0.0515	0.0535	0.0847
300	—	37	0.090	0.630	0.312	0.0429	0.0446	0.0707
350	—	37	0.097	0.681	0.364	0.0367	0.0382	0.0605
400	—	37	0.104	0.728	0.416	0.0321	0.0331	0.0529
500	—	37	0.116	0.813	0.519	0.0258	0.0265	0.0424
600	—	61	0.992	0.893	0.626	0.0214	0.0223	0.0353
700	—	61	0.107	0.964	0.730	0.0184	0.0189	0.0303
750	—	61	0.111	0.998	0.782	0.0171	0.0176	0.0282
800	—	61	0.114	1.03	0.834	0.0161	0.0166	0.0265
900	—	61	0.122	1.09	0.940	0.0143	0.0147	0.0235
1000	—	61	0.128	1.15	1.04	0.0129	0.0132	0.0212
1250	—	91	0.117	1.29	1.30	0.0103	0.0106	0.0169
1500	—	91	0.128	1.41	1.57	0.00858	0.00883	0.0141
1750	—	127	0.117	1.52	1.83	0.00735	0.00756	0.0121
2000	—	127	0.126	1.63	2.09	0.00643	0.00662	0.0106

Fig. 6–33 Reading *Table 8* (Chapter 9) for the circular-mil area of conductors when sized by number, as in figure 6–32. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright © 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

The total cross-sectional area is 423,200 circular mils per phase. The size of the grounding electrode conductor is taken directly from *Table 250-94* and is No. 1/0 copper, as indicated in figure 6–34. Note that in figure 6–34, part of the title of *Table 250-94* is *"Equivalent Area for Parallel Conductors."*

Figure 6–35 illustrates the use of service-entrance conductors in parallel for a grounded system, with a cross-sectional area exceeding the maximum listed in *Table 250-94*. The service consists of three 600 MCM copper conductors per phase for a three-phase, four-wire service. A copper grounding electrode conductor is used.

Table 250-94
Grounding Electrode Conductor for AC Systems

Size of Largest Service-Entrance Conductor or Equivalent Area for Parallel Conductors		Size of Grounding Electrode Conductor	
Copper	Aluminum or Copper-Clad Aluminum	Copper	*Aluminum or Copper-Clad Aluminum
2 or smaller	0 or smaller	8	6
1 or 0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250 MCM	4	2
Over 3/0 thru 350 MCM	Over 250 MCM thru 500 MCM	2	0
Over 350 MCM thru 600 MCM	Over 500 MCM thru 900 MCM	0	3/0
Over 600 MCM thru 1100 MCM	Over 900 MCM thru 1750 MCM	2/0	4/0
Over 1100 MCM	Over 1750 MCM	3/0	250 MCM

Fig. 6–34 Reading *Table 250-94* for sizing the grounding electrode conductor for the service illustrated in figure 6–32. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright © 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

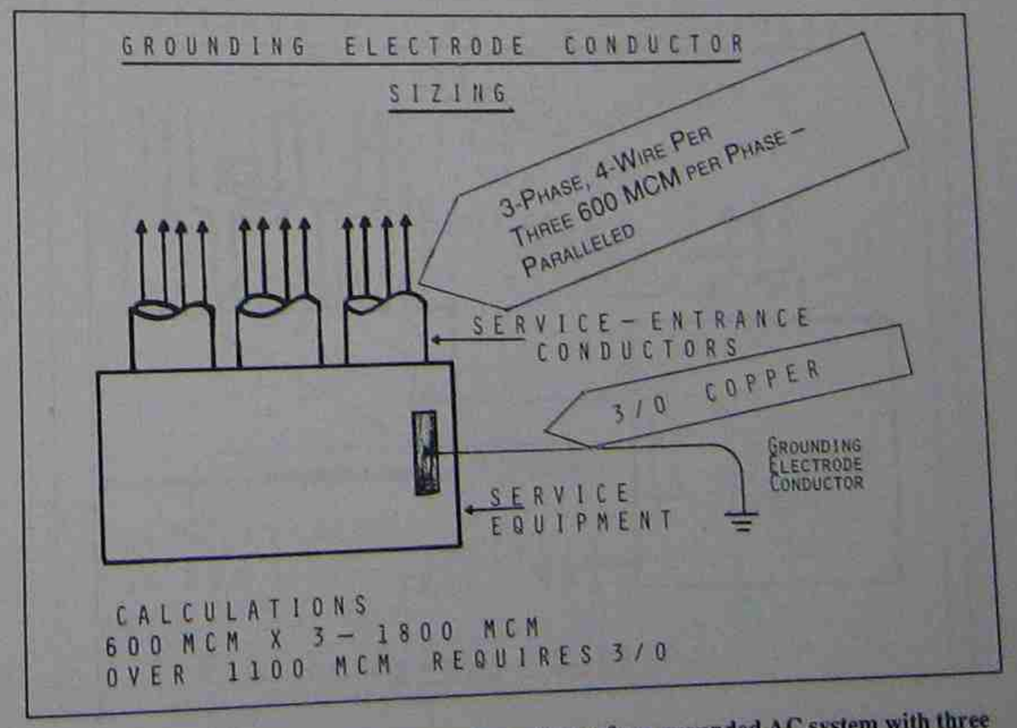

Fig. 6–35 Sizing the grounding electrode conductor for a grounded AC system with three

3 x 600 MCM = 1800 MCM per phase

This exceeds the 1100 MCM for the equivalent area of the service-entrance conductors listed in *Table 250-94*. In figure 6–36, the bottom line under "*Copper*" indicates that service-entrance conductors "over" 1100 MCM are not required to be larger than No. 3/0 copper.

Figure 6–37 illustrates a three-phase, 480-volt, three-wire ungrounded service with one 750 MCM copper conductor per phase. It is an ungrounded system and has no grounded service-entrance conductor. *Section 250-94* requires an ungrounded system, as well as a grounded system, to have a grounding electrode

Table 250-94
Grounding Electrode Conductor for AC Systems

Size of Largest Service-Entrance Conductor or Equivalent Area for Parallel Conductors		Size of Grounding Electrode Conductor	
Copper	Aluminum or Copper-Clad Aluminum	Copper	*Aluminum or Copper-Clad Aluminum
2 or smaller	0 or smaller	8	6
1 or 0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250 MCM	4	2
Over 3/0 thru 350 MCM	Over 250 MCM thru 500 MCM	2	0
Over 350 MCM thru 600 MCM	Over 500 MCM thru 900 MCM	0	3/0
Over 600 MCM thru 1100 MCM	Over 900 MCM thru 1750 MCM	2/0	4/0
Over 1100 MCM	Over 1750 MCM	3/0	250 MCM

Fig. 6–36 Reading *Table 250-94* for sizing the grounding electrode conductor for the service illustrated in figure 6–35. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright © 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

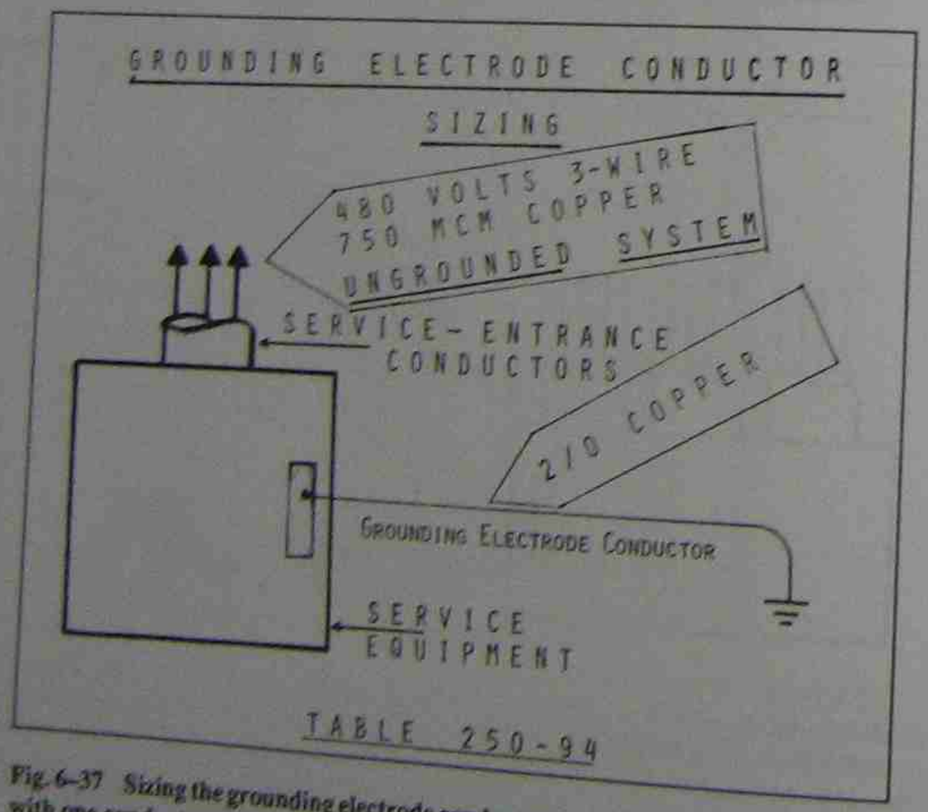

Fig. 6–37 Sizing the grounding electrode conductor for an ungrounded AC system with one conductor per phase and all conductors

conductor. As illustrated in figure 6–38, the grounding electrode conductor is read directly from *Table 250-94* and is No. 2/0 copper. Note the title of *Table 250-94*: "*Grounding Electrode Conductors for AC Systems.*" The term *AC systems* will include both the grounded and ungrounded AC system.

Figure 6–39 illustrates a three-phase, 4-volt, three-wire ungrounded service with three 750 MCM aluminum conductors in parallel

Table 250-94
Grounding Electrode Conductor for AC Systems

Size of Largest Service-Entrance Conductor or Equivalent Area for Parallel Conductors		Size of Grounding Electrode Conductor	
Copper	Aluminum or Copper-Clad Aluminum	Copper	*Aluminum or Copper-Clad Aluminum
2 or smaller	0 or smaller	8	6
1 or 0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250 MCM	4	2
Over 3/0 thru 350 MCM	Over 250 MCM thru 500 MCM	2	0
Over 350 MCM thru 600 MCM	Over 500 MCM thru 900 MCM	0	3/0
Over 600 MCM thru 1100 MCM	Over 900 MCM thru 1750 MCM	2/0	4/0
Over 1100 MCM	Over 1750 MCM	3/0	250 MCM

Fig. 6–38 Reading *Table 250-94* for sizing the grounding electrode conductor for the service illustrated in figure 6–37. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright © 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

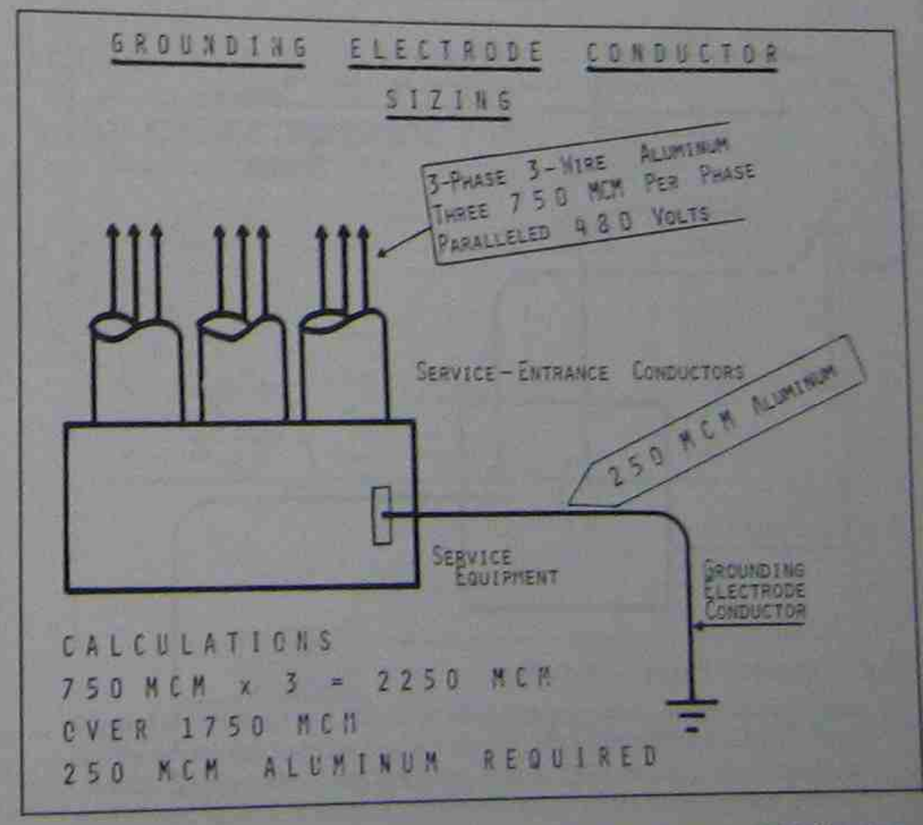

Fig. 6–39 Sizing the grounding electrode conductor for an ungrounded AC system with one conductor per phase, paralleled, and all conductors are aluminum.

Table 250-94
Grounding Electrode Conductor for AC Systems

Size of Largest Service-Entrance Conductor or Equivalent Area for Parallel Conductors		Size of Grounding Electrode Conductor	
Copper	Aluminum or Copper-Clad Aluminum	Copper	*Aluminum or Copper-Clad Aluminum
2 or smaller	0 or smaller	8	6
1 or 0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250 MCM	4	2
Over 3/0 thru 350 MCM	Over 250 MCM thru 500 MCM	2	0
Over 350 MCM thru 600 MCM	Over 500 MCM thru 900 MCM	0	3/0
Over 600 MCM thru 1100 MCM	Over 900 MCM thru 1750 MCM	2/0	4/0
Over 1100 MCM	Over 1750 MCM	3/0	250 MCM

Fig. 6–40 Reading *Table 250-94* for sizing the grounding electrode conductor for the service illustrated in figure 6–39. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright © 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

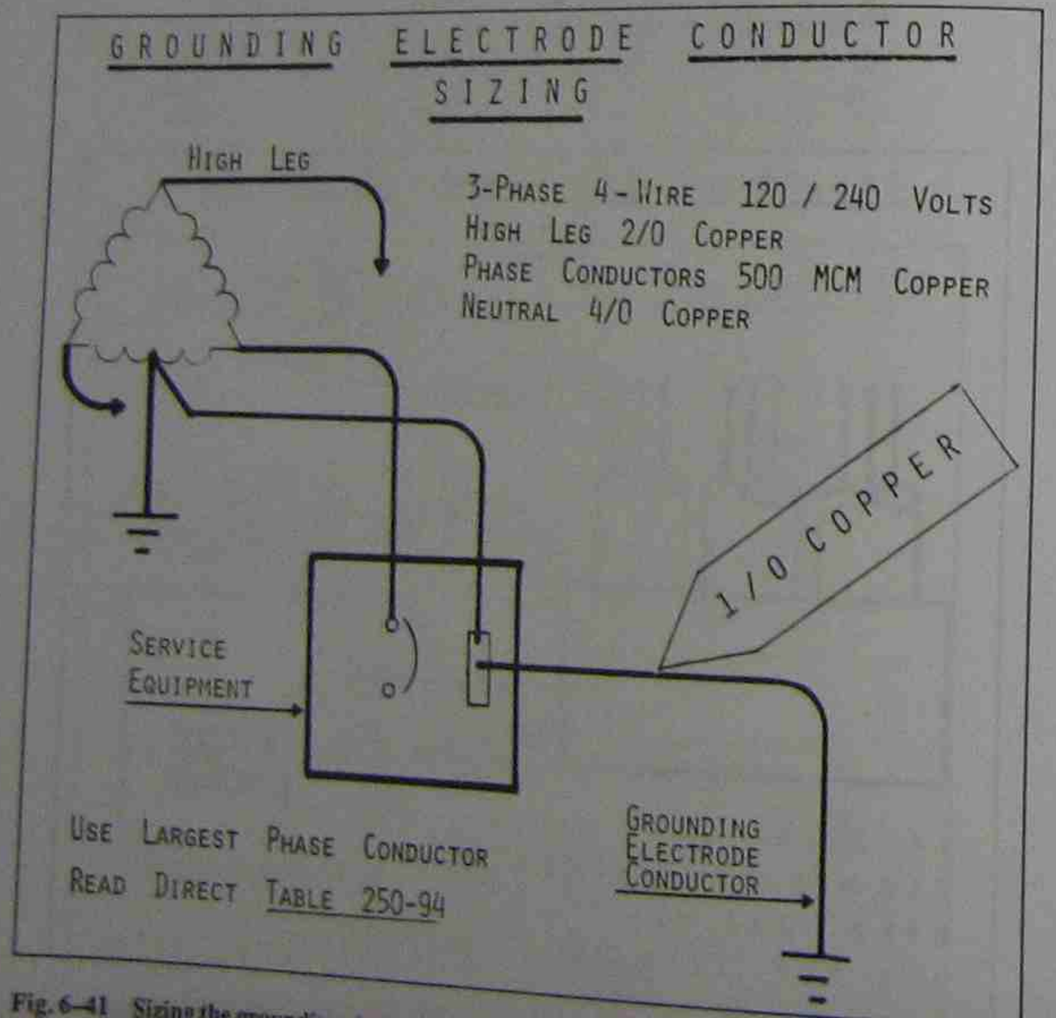

Fig. 6–41 Sizing the

phase, with an aluminum grounding electrode conductor.

750 MCM x 3 conductors = 2250 MCM per phase

The size of the grounding electrode conductor is read directly from *Table 250-94* (figure 6–40). The 2250 MCM is over the largest size listed for aluminum. Therefore, the grounding electrode conductor is 250 MCM aluminum.

Figure 6–41 illustrates a three-phase, 240/120-volt grounded system with a high leg; all copper conductors are used. The high leg is calculated to be No. 2/0, the other two phase conductors are 500 MCM, and the neutral is No. 4/0. The grounding electrode conductor is calculated on the largest service-entrance conductor, which in this case is 500 MCM copper.

The size of the copper grounding electrode conductor is read directly from *Table 250-94*, as illustrated in figure 6–42, and is No. 1/0 copper.

Figure 6–43 illustrates the use of aluminum service-entrance conductors and a different metal, copper, for the grounding electrode conductor. It is a three-phase, three-wire, 480-volt system with one 750 MCM aluminum conductor per phase, with a copper grounding electrode conductor. The Code makes no mention of this very common installation and *Table 250-94* can be used as illustrated in figure 6–42. The size of the service-entrance conductor is read under "Aluminum" and the size of the grounding electrode conductor is read under "Copper." It is No. 1/0 copper.

CAUTION: This only applies to the grounding electrode conductor. Other grounding conductors are handled differently.

Table 250-94
Grounding Electrode Conductor for AC Systems

Size of Largest Service-Entrance Conductor or Equivalent Area for Parallel Conductors		Size of Grounding Electrode Conductor	
Copper	Aluminum or Copper-Clad Aluminum	Copper	*Aluminum or Copper-Clad Aluminum
2 or smaller	0 or smaller	8	6
1 or 0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250 MCM	4	2
Over 3/0 thru 350 MCM	Over 250 MCM thru 500 MCM	2	0
Over 350 MCM thru 600 MCM	Over 500 MCM thru 900 MCM	0	3/0
Over 600 MCM thru 1100 MCM	Over 900 MCM thru 1750 MCM	2/0	4/0
Over 1100 MCM	Over 1750 MCM	3/0	250 MCM

Fig. 6–42 Reading *Table 250-94* for sizing the grounding electrode conductor for the service illustrated in figure 6–41. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright © 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official

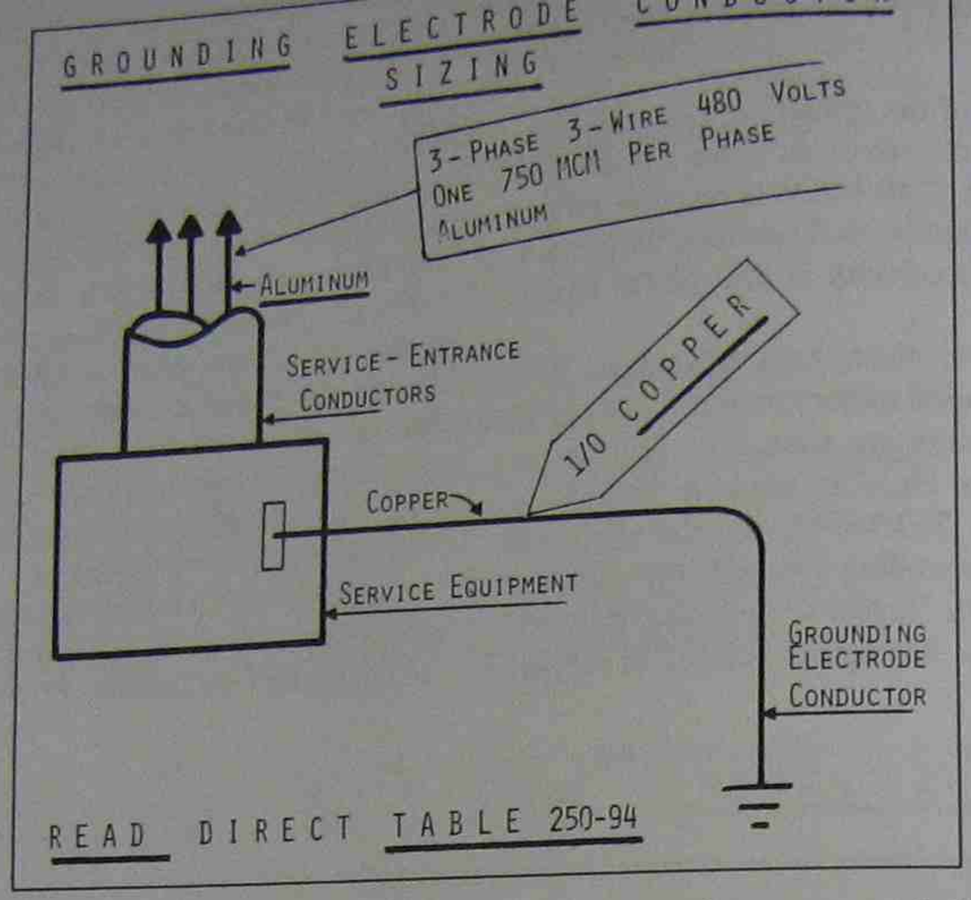

Fig. 6–43 **Sizing the grounding electrode conductor for an ungrounded system with aluminum service-entrance conductors and a copper grounding electrode conductor.**

Table 250-94
Grounding Electrode Conductor for AC Systems

Size of Largest Service-Entrance Conductor or Equivalent Area for Parallel Conductors		Size of Grounding Electrode Conductor	
Copper	Aluminum or Copper-Clad Aluminum	Copper	*Aluminum or Copper-Clad Aluminum
2 or smaller	0 or smaller	8	6
1 or 0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250 MCM	4	2
Over 3/0 thru 350 MCM	Over 250 MCM thru 500 MCM	2	0
Over 350 MCM thru 600 MCM	Over 500 MCM thru 900 MCM	0	3/0
Over 600 MCM thru 1100 MCM	Over 900 MCM thru 1750 MCM	2/0	4/0
Over 1100 MCM	Over 1750 MCM	3/0	250 MCM

Fig. 6–44 **Reading *Table 250-94* for sizing the grounding electrode conductor for the service illustrated in figure 6–43.** Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright © 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

SUMMARY

The grounding electrode conductor is the main highway the electrons travel to get to the grounding electrode and into the ground. All other grounding conductors are feeder lines to the main highway.

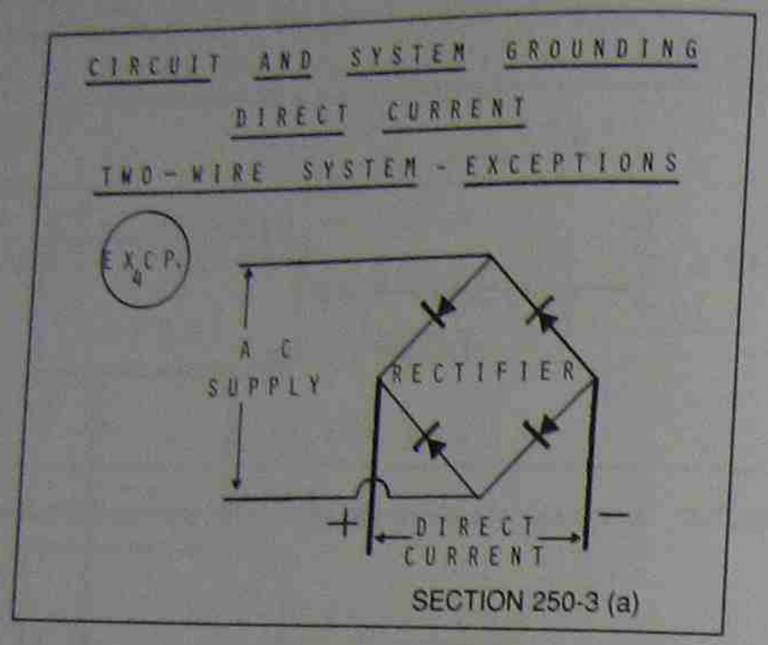

Fig. 7–9 An example of an ungrounded, two-wire DC system secured with the use of rectifiers.

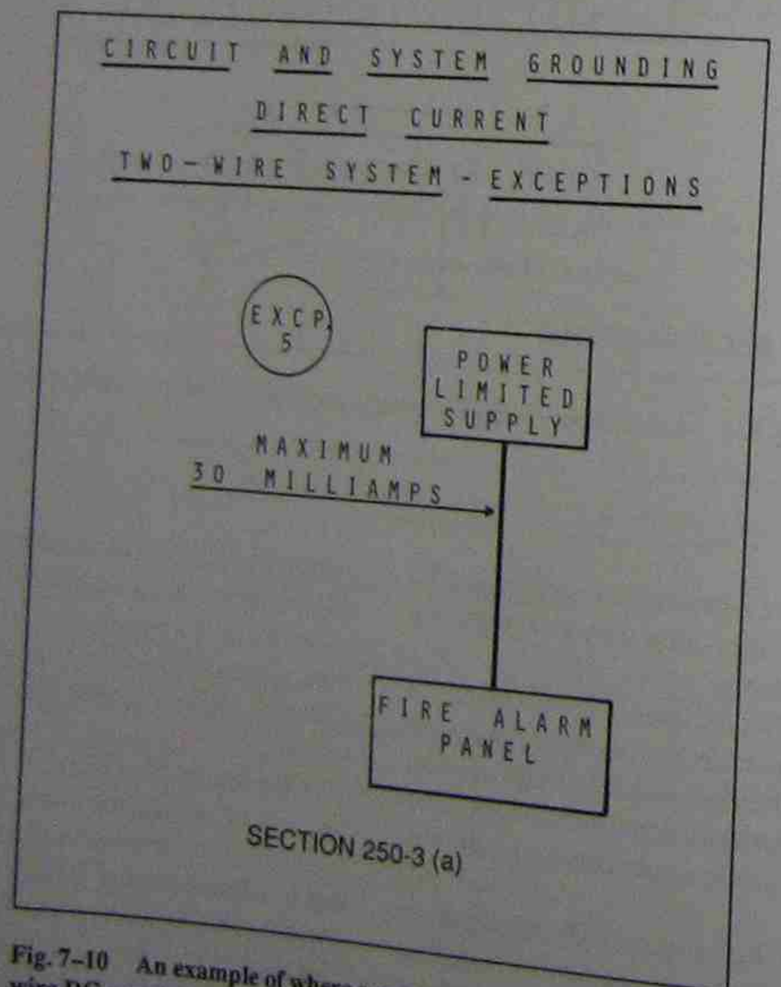

Fig. 7–10 An example of where a power-limited wire DC supply is permitted.

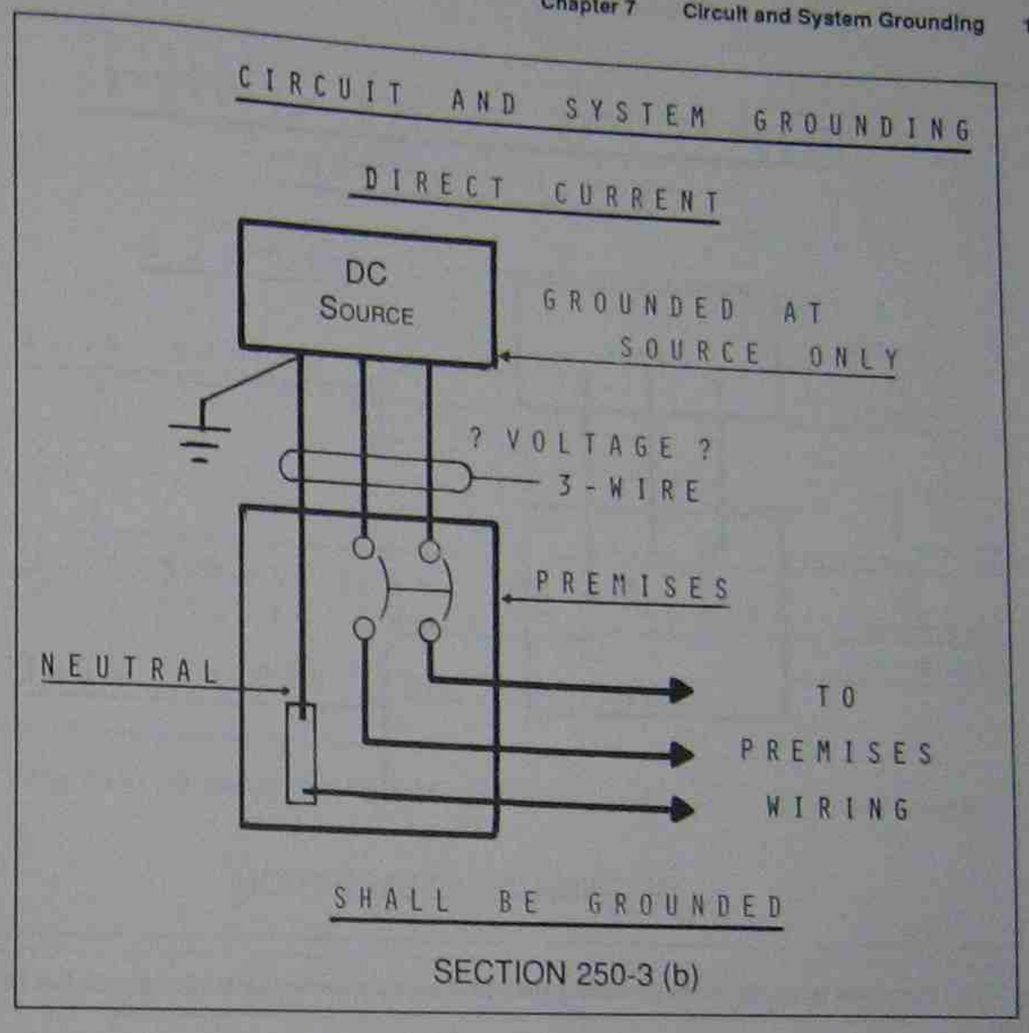

Fig. 7–11 Requirements for grounding a three-wire DC system.

This exception coordinates the Code regulations with *Article 760*.

Section 250-3(b) (figure 7–11) requires the neutral conductor of all three-wire, direct-current systems that supply premises wiring to be grounded. There are no minimum or maximum voltages mentioned, nor are there any exceptions listed. Once again, the grounding electrode conductor is installed at the source of supply only when it is located other than on the premises. The grounded conductor is not bonded to a second grounding electrode conductor at the service as it is in the case of alternating-current grounded systems.

electrode conductor of direct-current systems be installed at the direct-current generator, or the first disconnecting means or overcurre protective device. This applies when the direc current source is located on the premises.

ALTERNATING-CURRENT SYSTEMS

The Code divides the alternating-curre systems to be grounded into three groups. The are:

1. Systems operating at less than 50 volts
2. Systems operating at 50 volts to 1000 vo

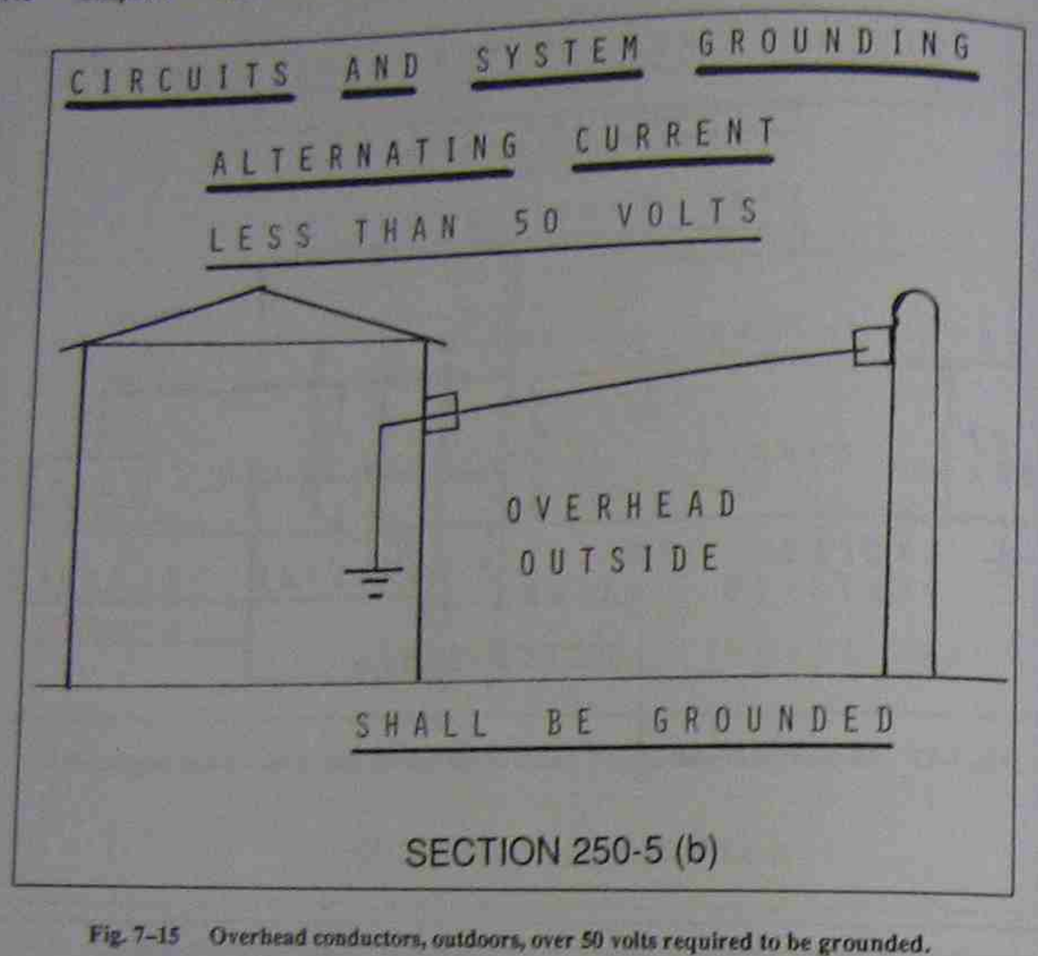

Fig. 7–15 Overhead conductors, outdoors, over 50 volts required to be grounded.

design engineer should decide whether such a system should be grounded. An example here would be where the primary of a transformer is supplied with 120 volts, one hot wire, and a neutral, and the secondary is 32 volts. The secondary is less than 50 volts and the voltage supplying the transformers does not exceed 150 volts to ground (figure 7–16). In this case, the 32-volt secondary is not required to be grounded, but it is permitted to be grounded.

Alternating-Current Systems of 50 to 1000 Volts

Here the Code offers three electrical distribution systems and one situation under which the system shall be grounded. It should be kept in mind that these are not the only systems or situations under which a grounded system is permitted to be installed. Rather, these are the "shall"-be-grounded systems, although other systems are permitted to be grounded.

Section 250-5(b) (1) requires that where the system can be so grounded, the maximum voltage to ground on the ungrounded conductors does not exceed 150 volts. Figure 7–17 illustrates the three most common applications of this regulation, which are the most common grounded systems the average electrician works on almost daily.

Figure 7–17 (a) shows the single-phase, 120-volt, two-wire system where one conductor is intentionally grounded and the voltage to ground does not exceed 150 volts. Such a system would be used for a small service with a single branch circuit.

In figure 7–17 (b), the single-phase, 120/240-volt, three-wire system is shown, with the center tap of the transformer intentionally grounded and used as the neutral conductor.

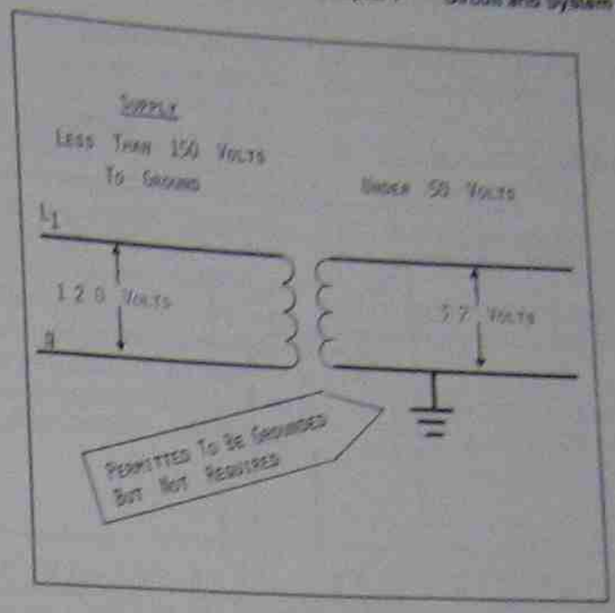

Fig. 7–16 AC system permitted to be grounded.

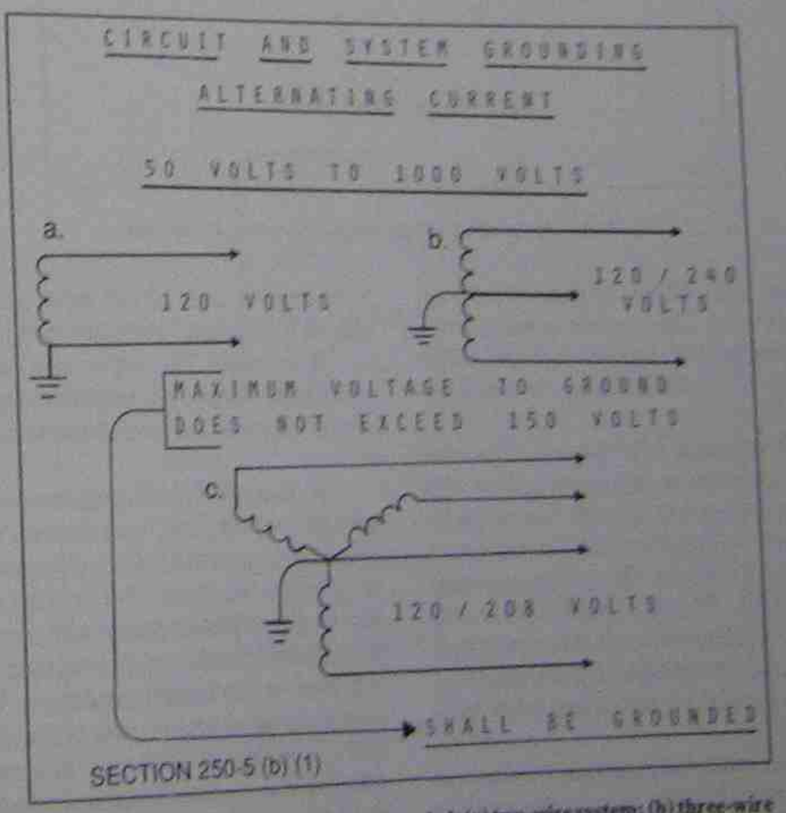

Fig. 7–17 AC systems required to be grounded: (a) two-wire system; (b) three-wire system; (c) four-wire system.

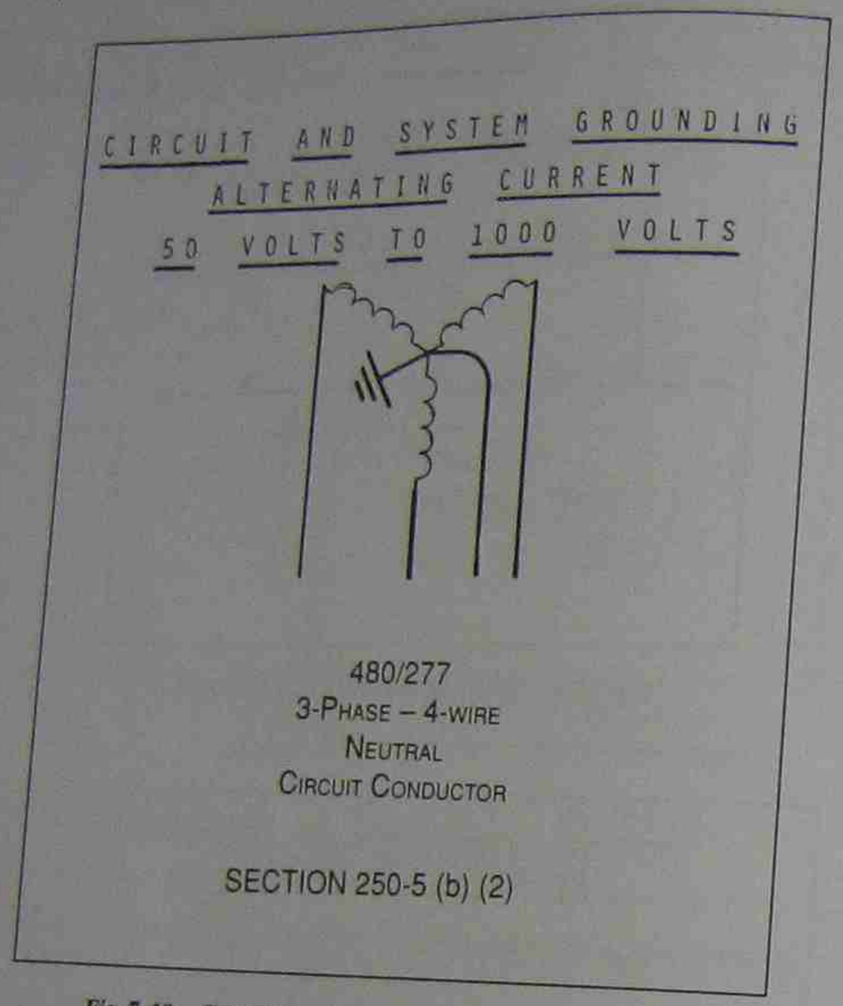

Fig. 7–18 Grounding a three-phase, four-wire, AC system.

Once again, the voltage to ground does not exceed 150 volts. This system is extensively used for residential services and in office areas where 120 volts is needed for receptacles.

The three-phase, 120/208-volt, four-wire system, which is a wye connected system with the wye point of the system intentionally grounded and used as the neutral conductor, is shown in figure 7–17 (c). The voltage to ground does not exceed 150 volts. This system is used for services and distribution in office buildings, warehouses, shopping strips, schools, churches, multifamily dwellings, and many other locations.

In each of these three systems, the situation such that the system can be grounded with the oltage to ground not exceeding 150 volts. Therefore, in each of the three systems, the system is "required" to be grounded.

Remember: The higher the voltage, the smaller the current. The smaller the current, the smaller the wire. The smaller the wire, the lower the cost.

Section 250-5 (b) (2) requires the 480/277-volt, three-phase, four-wire system, where the neutral conductor is used as a circuit conductor, to be grounded (figure 7–18). This system is also a wye connected system with the wye point of the system intentionally connected to ground and used as the neutral conductor. When the term *nominally rated* is used, it also means the rule covers the 460/266-volt system and the 440/254-volt system. This system is used extensively for lighting in schools, high-rise office buildings, and industrial areas.

Section 250-5 (b) (3) applies to a specific system and requires it to be grounded (figure 7–19). This system is the three-phase, delta, 120/240-volt, four-wire system, which is accomplished by intentionally grounding the center tap of one transformer of a three-phase, delta-connected transformer bank. The system is known as a "high leg," "wild leg," or "red leg." The more technical identification is "delta with a high leg." The reason it is called the "high leg" is that one phase has a much higher voltage reading to ground than either of the other two legs. However, the voltage is still less than the phase-to-phase voltage. In *Section 384-3 (f)*, the Code requires the high leg to be the "B" phase. The two most common system voltages for this connection are:

1. The 120/240-volt system will have a high-leg voltage of 208 volts.
2. The 110/220-volt system will have a high-leg voltage of 190 volts.

A simple way to calculate the high-leg voltage is to multiply half the phase voltage by 1.73.

(240/2 = 120 × 1.73 = 208 volts)
(220/2 = 110 × 1.73 = 190 volts)

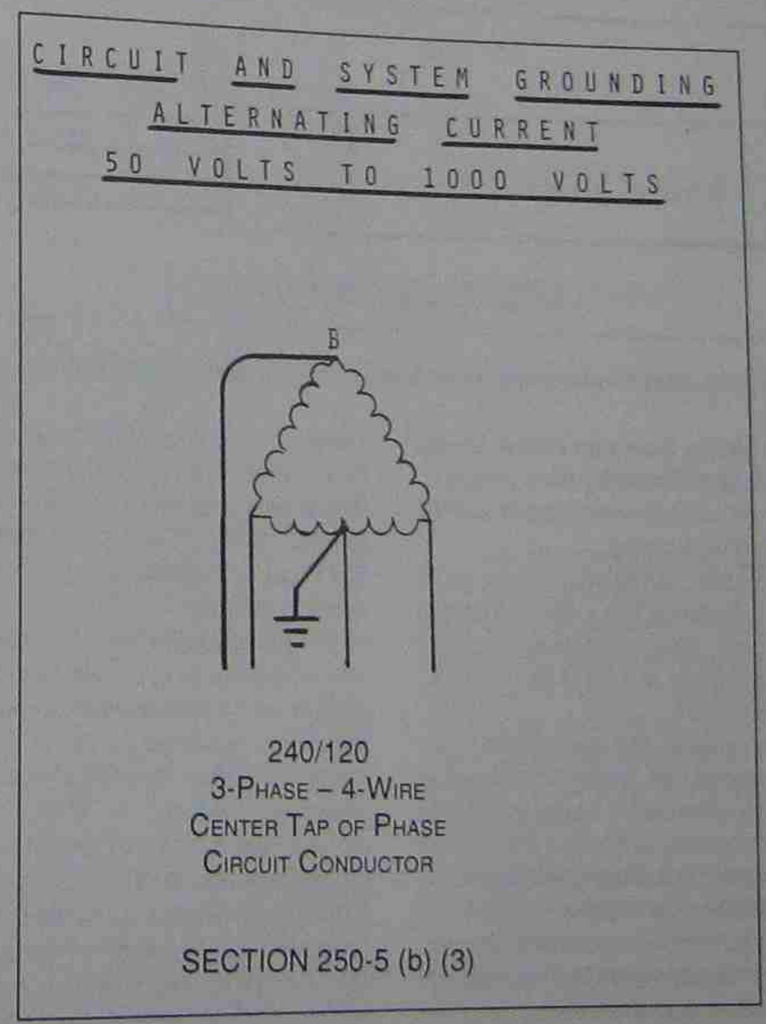

Fig. 7–19 Grounding a three-phase, four-wire, delta AC system with a high leg.

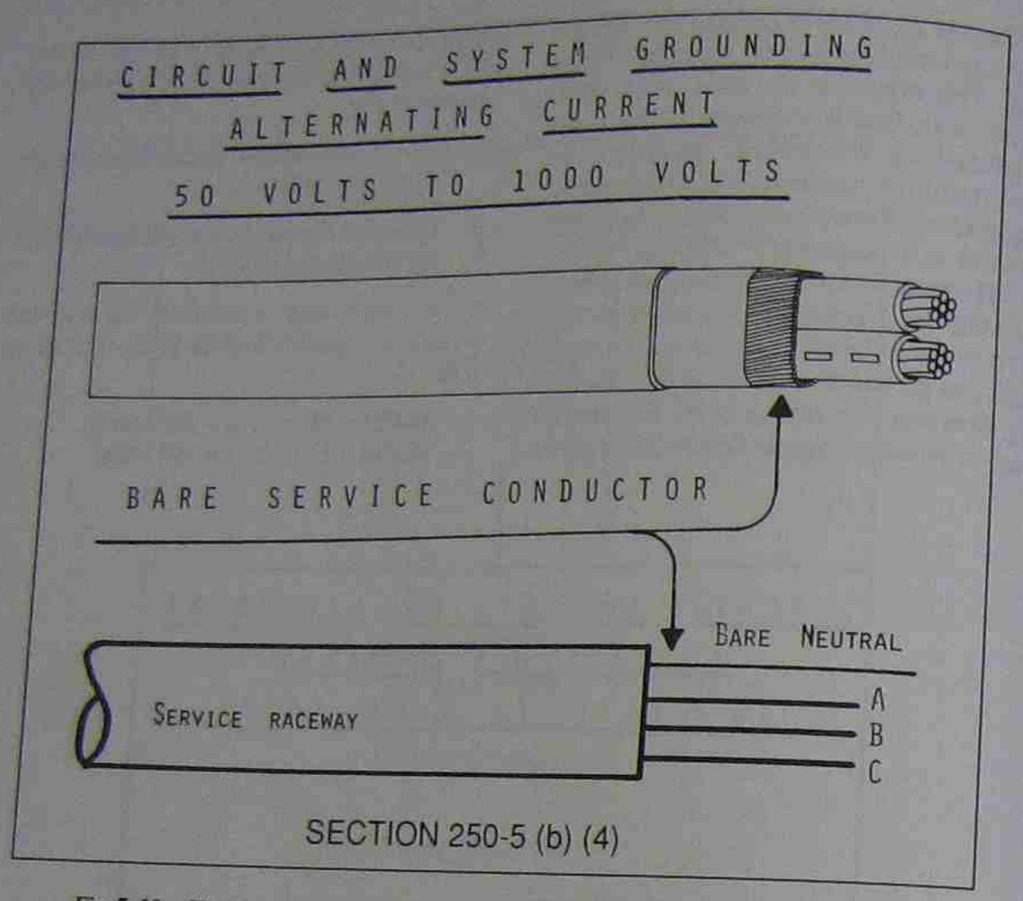

Fig. 7–20 The bare conductor in service-entrance cable is required to be grounded.

The three-phase, four-wire system is used where there is a need for both power and lighting. The three-phase is used for power and the 120 volts is used for lighting.

CAUTION: No 120-volt lighting is to be connected to the high leg. The Code permits the use of the high-leg voltage, but there is seldom a situation where there is a need for a single-phase, 208-volt circuit.

The Code requires the above-listed systems to be grounded, but it also permits other alternating-current systems to be grounded. The Code also calls attention to the fact that the use of ground detectors with ungrounded systems can provide additional protection.

Section 250-5 (b) (4) has to do with uninsulated neutral service-entrance conductors (figure 7–20), and is one of the many just plain common-sense rules in the Code. When an uninsulated grounded conductor is installed as a service-entrance conductor, the uninsulated or bare conductor shall be a grounded conductor. This also coordinates the Code with *Article 230 (230-22, 230-30, 230-41)*, which permits the use of an uninsulated neutral as a service-entrance conductor.

This regulation actually prohibits using a service-entrance cable with two insulated conductors, and one uninsulated conductor under a common jacket being used for the service-entrance conductors for a three-phase, three-wire, ungrounded system.

Section 250-5 (b) lists five exceptions permitting 50-to-1000-volt systems to operate without a grounded conductor. These exceptions are discussed in the following paragraphs.

Exception No. 1 (figure 7–21) permits a system used exclusively to supply industrial electric furnaces for melting, refining, tempering, and the like to be installed without the

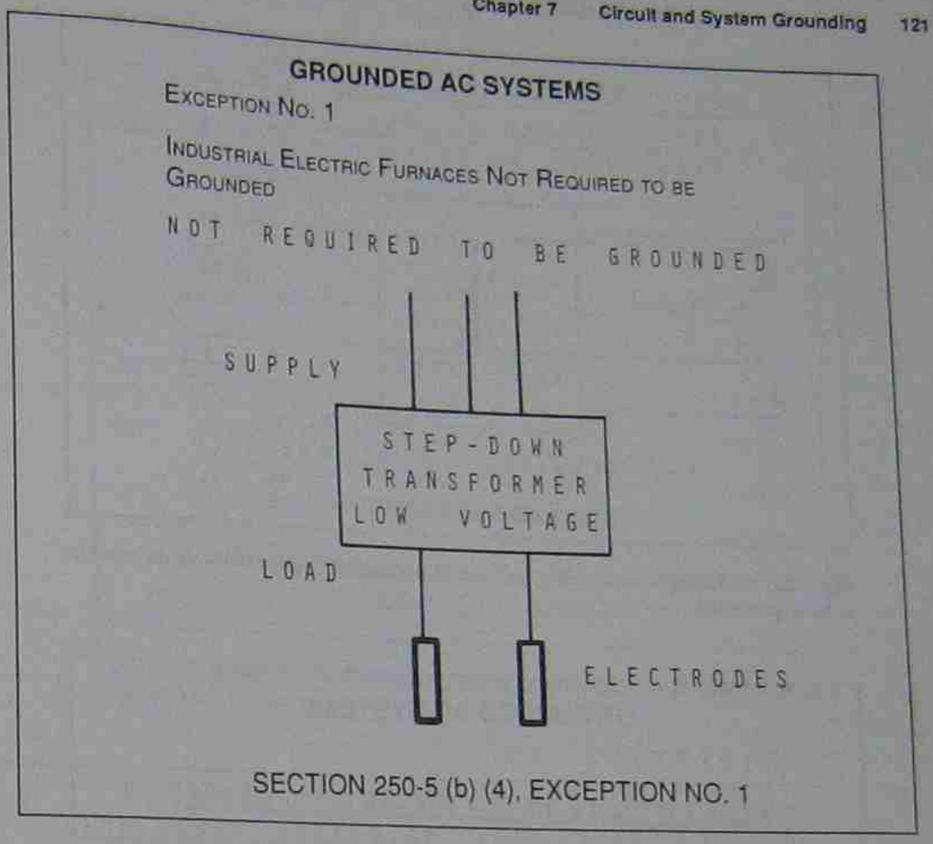

Fig. 7–21 An example of Exception No. 1, which permits a 50-volt to 1000-volt AC system to be ungrounded.

system being grounded. Exception No. 2 (figure 7–22) permits a separately derived system used exclusively for rectifiers supplying only adjustable-speed industrial drives to be installed without the system being grounded.

Exception No. 3 (figure 7–23) permits a separately derived system supplied by transformers to be installed without the system being grounded, provided that all five of the conditions listed are fulfilled. One condition requires the use of ground detectors. Figure 7–23 also illustrates the use of ground detectors, with lights used to warn of a ground being detected.

In more than one place, the Code calls attention to the value of installing ground detectors. The ground detector can be used to give a visual warning, an audible warning, or a combination of both when there is an accidental ground on the circuit. This allows corrective measures to be taken before the ground can develop into a serious fault.

Isolation transformer. Exception No. 4 coordinates the Code with *Article 517 (Health Care Facilities)*, where ungrounded systems are permitted for the purpose of isolating a circuit from ground. Figure 7–24 illustrates the use of an isolating transformer, whose purpose is to protect against any possible circulating ground currents and to help eliminate noise on computer circuits.

High-impedance grounding. Exception No. 5 (figure 7–25) is an example of how impedance grounding is used to limit the ground fault current to a low value by the use of an impedance, which is usually a resistor. Exception No. 5 of *Section 250-5 (b)* permits the use of a high-impedance grounded neutral system, but

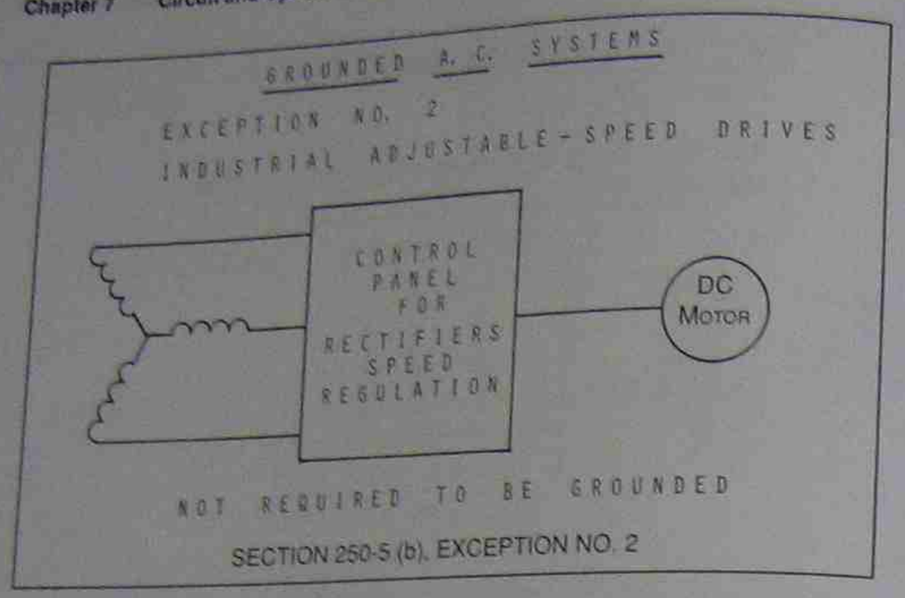

Fig. 7–22 An example of Exception No. 2, which permits a 50-volt to 1000-volt AC system to be ungrounded.

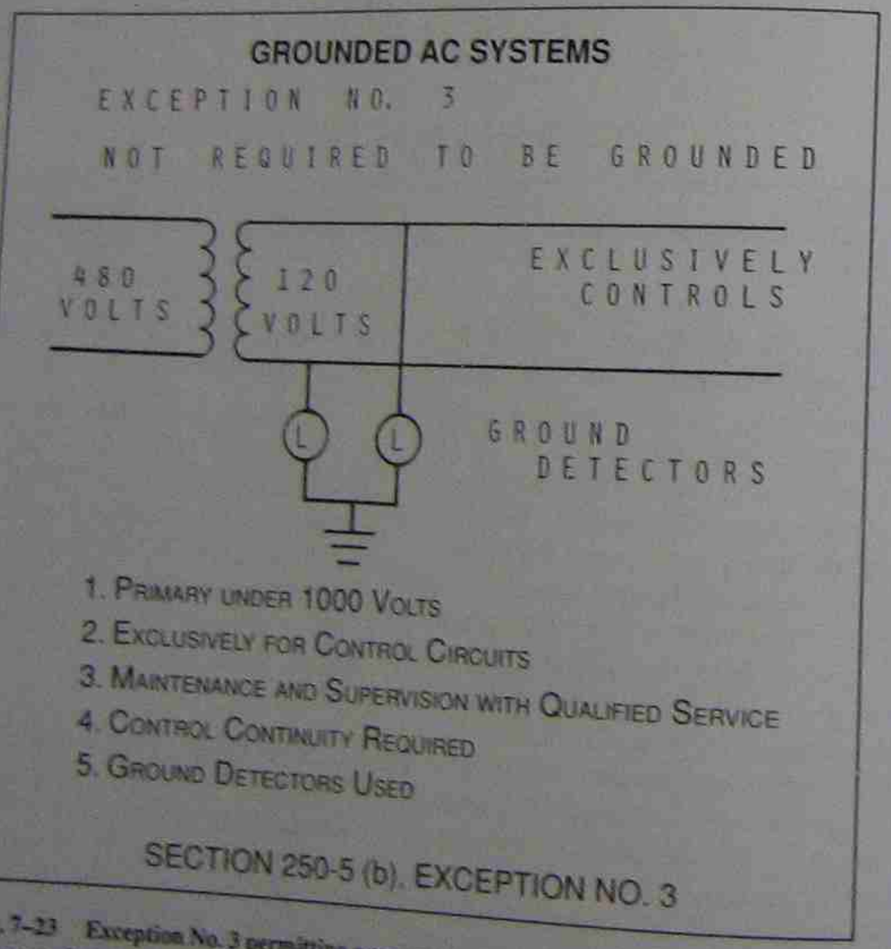

Fig. 7–23 Exception No. 3 permitting a separately derived AC system used exclusively for controls to be ungrounded.

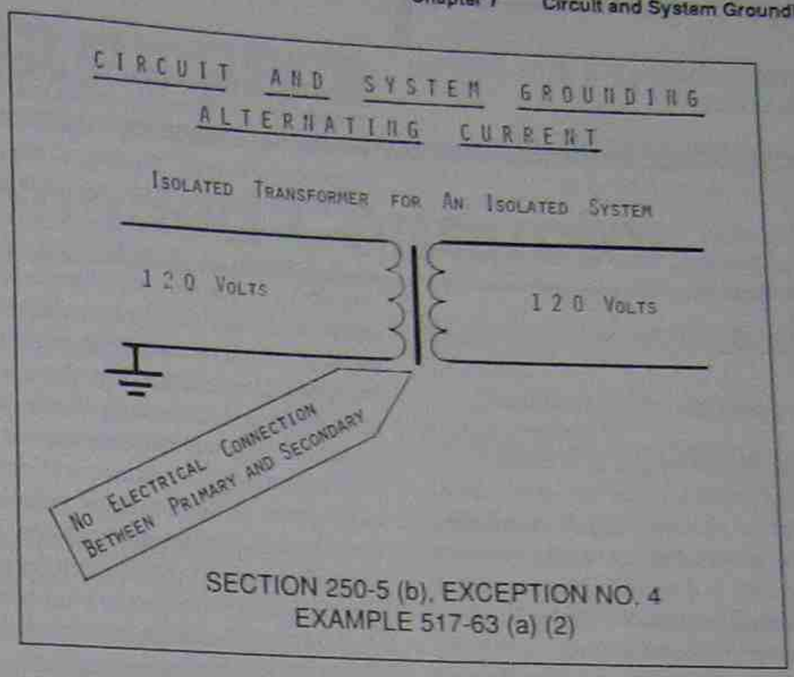

Fig. 7–24 Exception No. 4 permitting use of an isolation transformer for an ungrounded AC system.

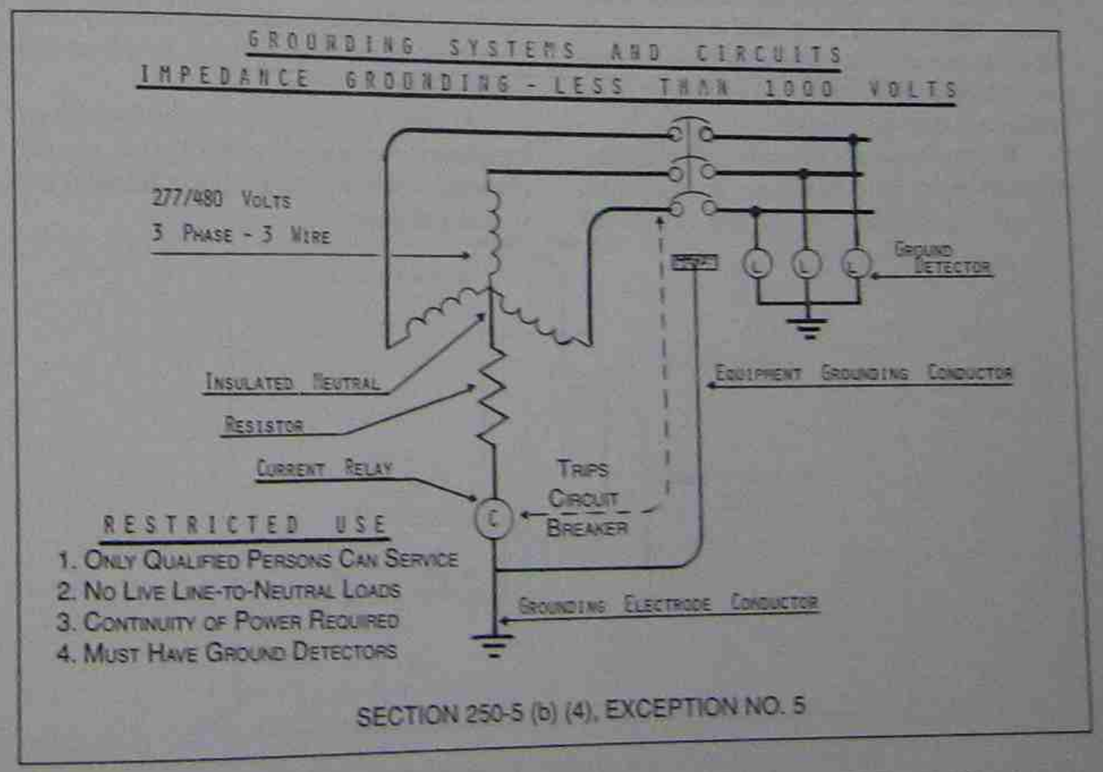

Fig. 7–25 Exception No. 5 permitting the use of impedance grounding for a 277/480-volt AC system.

becomes an equipment grounding conductor from the service back to the source. The

grounded conductor to the grounding electrode conductor. This requires a lot of interlocking and referencing with other parts of *Article 250*.

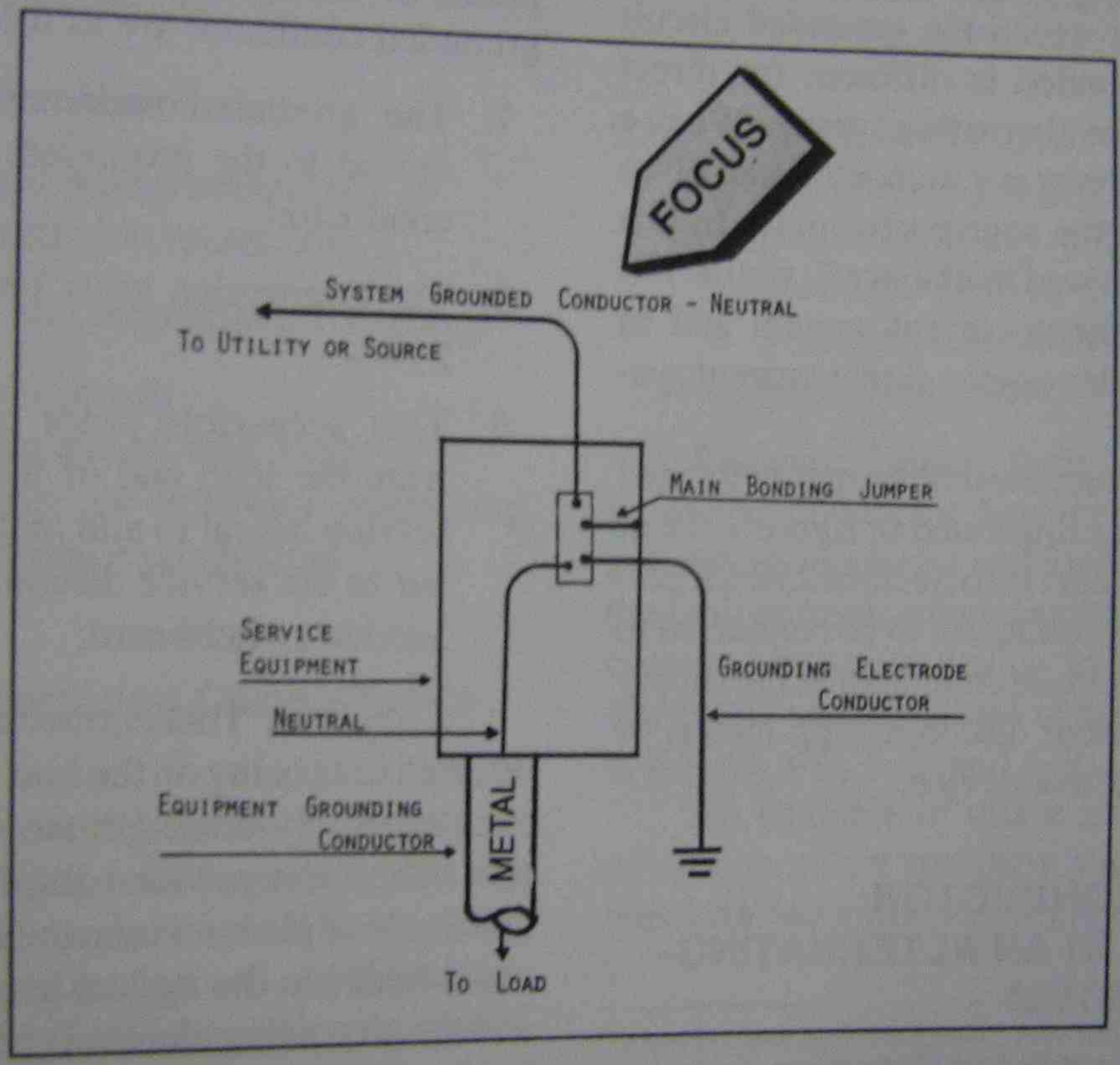

Fig. 8–1 Focusing on the system grounded conductor (neutral).

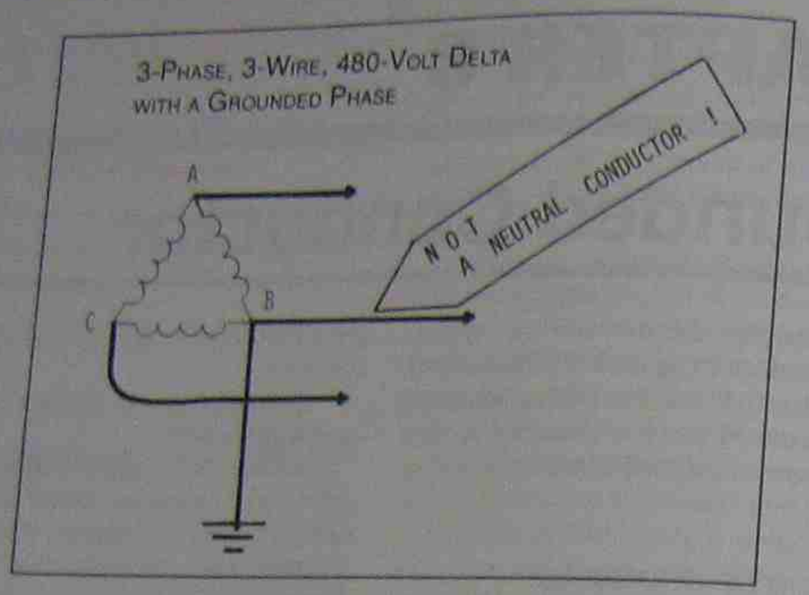

Fig. 8–2 A delta with a grounded leg that is not a neutral.

GROUNDED CONDUCTOR CONNECTION IN A DIRECT-CURRENT SYSTEM

The point at which the grounded circuit conductor is grounded is different for direct current than it is for alternating current. When a direct-current system is grounded, it shall be grounded only at the source of supply. In this book, this is illustrated in chapter 7, figure 7–5 for a two-wire, direct-current system and in figure 7–11 for a three-wire, direct-current system.

When the direct-current supply is located on the premises, as illustrated in figure 7–12 of chapter 7, the exception to *Section 250-22* permits the grounded conductor to be connected to the grounding electrode conductor at the supply or at the first system disconnecting means or overcurrent protective device.

GROUNDED CONDUCTOR CONNECTION IN AN ALTERNATING-CURRENT SYSTEM

When a grounded AC system is used, *Section 250-23(a)* requires the grounded conductor to be connected to the grounding electrode system by means of the grounding electrode conductor. Figure 8–3 illustrates where the connection shall be made. Some of the main points of *Section 250-23(a)* that apply to the grounded conductor are as follows:

1. The grounded conductor shall be connected to the grounded (neutral) service conductor.
2. The connection must be at an accessible point.
3. That accessible point can be anywhere from the load end of the service drop or service lateral to and including the neutral bar in the service disconnecting means or service switchboard.

Comment: This connection is more often referred to as being on the line side (also referred to as the supply side) of the service switch, or the line side of the service equipment. It permits a multitude of places where the connection can be made between the system grounded conductor and the grounding electrode conductor. The following are some of the main points concerning where the connection is usually made (figure 8–3)..

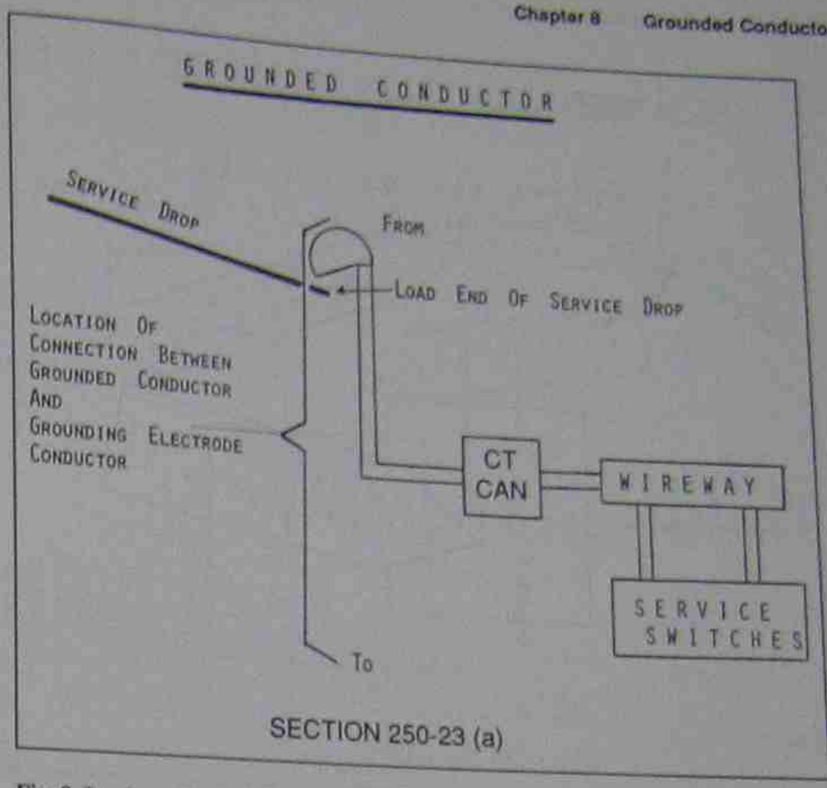

Fig. 8–3 Location of connection between the grounded conductor and the grounding electrode conductor.

1. Residential installations
   a. Service equipment neutral bar
   b. Also permitted in meter base
2. Commercial and industrial installations
   a. Service equipment
   b. CT (current transformer) can
   c. Metal gutter or wireway containing service-entrance conductors

Bringing the Grounded Conductor to Service

Where an alternating-current system operating at less than 1000 volts is grounded at any point, the grounded conductor shall be run to the service, as illustrated in figure 8–4. Therefore, any time the utility source of supply has a grounded conductor at the supply transformer, that conductor must be brought to the service equipment, whether it is used or not.

Quote – "Section 250-23(b). Where an ac system operating at less than 1000 volts is grounded at any point, the grounded conductor shall be run to each service. This conductor shall be routed with the phase conductors.'"*

Reason: Under fault conditions, the grounded conductor becomes the equipment grounding conductor and furnishes the path for the fault current, which causes the circuit overcurrent protective device to operate. This is illustrated and explained under *Faults* (chapter 4, figures 4–7, 4–8, and 4–9).

An example of this would be a situation where the utility company supply transformer was 120/240 volts with a grounded center tap.

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Table 8. Conductor Properties

Size AWG/ MCM	Area Cir. Mils	DC Resistance at 75°C, 167°F						
		Stranding		Overall		Copper		Aluminum
		Quantity	Diam. In.	Diam. In.	Area In.²	Uncoated ohm/MFT	Coated ohm/MFT	ohm/ MFT
18	1620	1	—	0.040	0.001	7.77	8.08	12.8
18	1620	7	0.015	0.046	0.002	7.95	8.45	13.1
16	2580	1	—	0.051	0.002	4.89	5.08	8.05
16	2580	7	0.019	0.058	0.003	4.99	5.29	8.21
14	4110	1	—	0.064	0.003	3.07	3.19	5.06
14	4110	7	0.024	0.073	0.004	3.14	3.26	5.17
12	6530	1	—	0.081	0.005	1.93	2.01	3.18
12	6530	7	0.030	0.092	0.006	1.98	2.05	3.25
10	10380	1	—	0.102	0.008	1.21	1.26	2.00
10	10380	7	0.038	0.116	0.011	1.24	1.29	2.04
8	16510	1	—	0.128	0.013	0.764	0.786	1.26
8	16510	7	0.049	0.146	0.017	0.778	0.809	1.28
6	26240	7	0.061	0.184	0.027	0.491	0.510	0.808
4	41740	7	0.077	0.232	0.042	0.308	0.321	0.508
3	52620	7	0.087	0.260	0.053	0.245	0.254	0.403
2	66360	7	0.097	0.292	0.067	0.194	0.201	0.319
1	83690	19	0.066	0.332	0.087	0.154	0.160	0.253
1/0	105600	19	0.074	0.373	0.109	0.122	0.127	0.201
2/0	133100	19	0.084	0.419	0.138	0.967	0.101	0.159
3/0	167800	19	0.094	0.470	0.173	0.0766	0.0797	0.126
4/0	211600	19	0.106	0.528	0.219	0.0608	0.0626	0.100
250	—	37	0.082	0.575	0.260	0.0515	0.0535	0.0847
300	—	37	0.090	0.630	0.312	0.0429	0.0446	0.0707
350	—	37	0.097	0.681	0.364	0.0367	0.0382	0.0605
400	—	37	0.104	0.728	0.416	0.0321	0.0331	0.0529
500	—	37	0.116	0.813	0.519	0.0258	0.0265	0.0424
600	—	61	0.992	0.893	0.626	0.0214	0.0223	0.0353
700	—	61	0.107	0.964	0.730	0.0184	0.0189	0.0303
750	—	61	0.111	0.998	0.782	0.0171	0.0176	0.0282
800	—	61	0.114	1.03	0.834	0.0161	0.0166	0.0265
900	—	61	0.122	1.09	0.940	0.0143	0.0147	0.0235
1000	—	61	0.128	1.15	1.04	0.0129	0.0132	0.0212
1250	—	91	0.117	1.29	1.30	0.0103	0.0106	0.0169
1500	—	91	0.128	1.41	1.57	0.00858	0.00883	0.0141
1750	—	127	0.117	1.52	1.83	0.00735	0.00756	0.0121
2000	—	127	0.126	1.63	2.09	0.00643	0.00662	0.0106

Fig. 8–9 Using *Table 8* (Chapter 9) to determine the nearest conductor size when the 12-1/2 percent rule is applied. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright ©, 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the

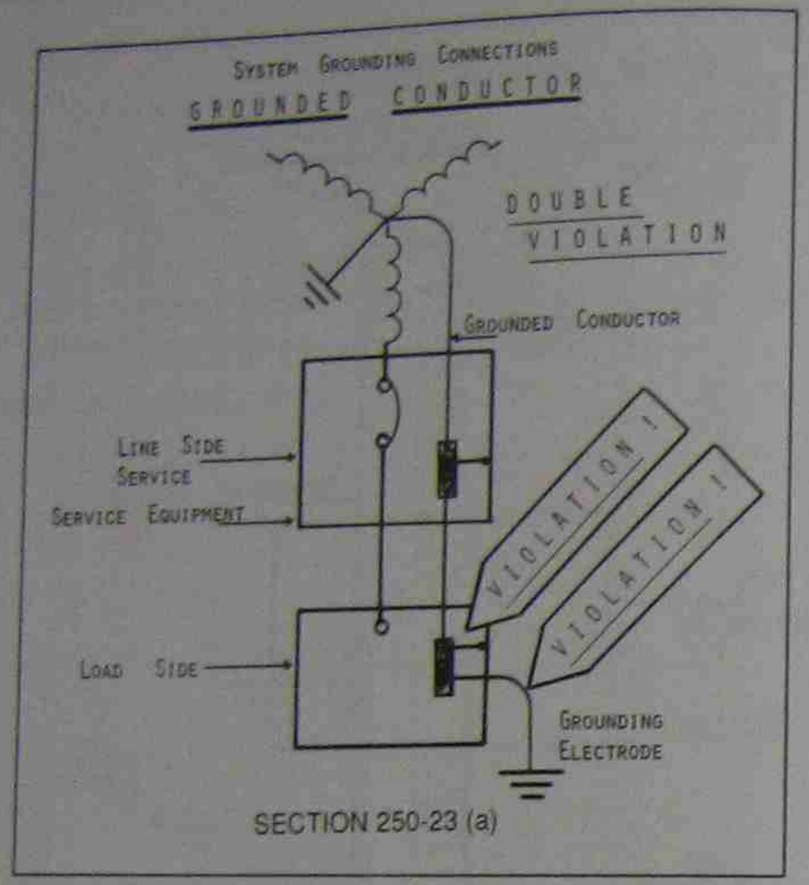

Fig. 8–11 Violation of basic rule for making a grounding connection to the grounded conductor.

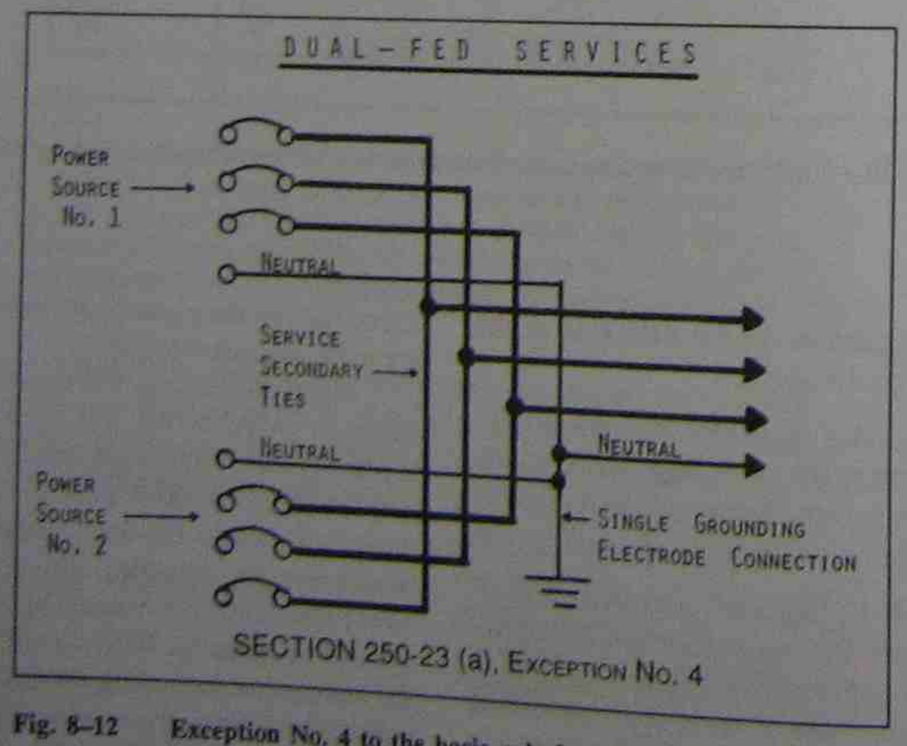

Fig. 8–12 Exception No. 4 to the basic rule for connecting the grounded conductor for a dual-fed system.

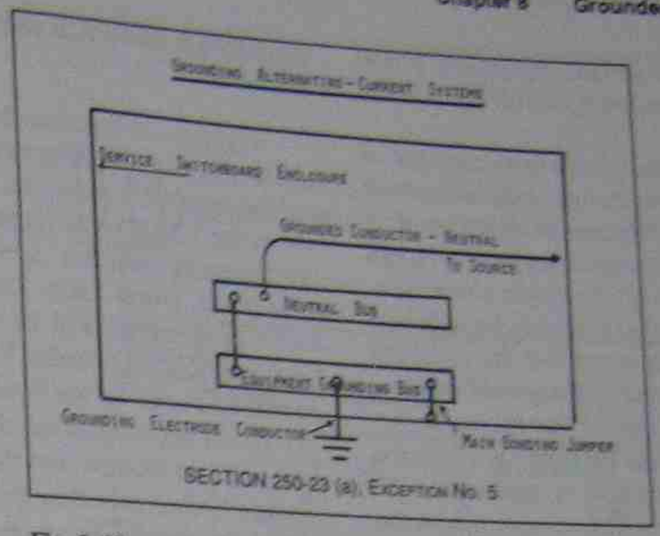

Fig. 8–13 An example of Exception No. 5 for connecting the grounded conductor to a service switchboard.

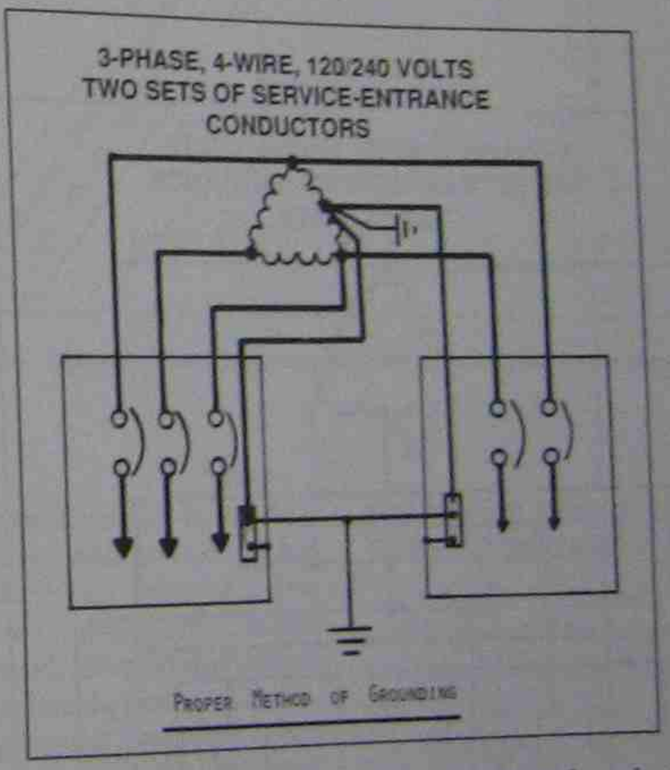

Fig. 8–14 The grounding connections for a three-phase, four-wire delta system when two separate distribution systems are applied.

Three-phase Delta with a High Leg

Figure 8–14 illustrates a situation where the three-phase power and the single-phase lighting service-entrance conductors are brought into the service equipment separately

leg. Note that the grounded conductor i
with the power conductors to the powe
equipment. It is also brought to the
service equipment. Both are connecte
use the same grounding electrode syst
grounded conductor is not brought to t
service equipment and there is a fault o

side of the power service equipment, it will create a higher impedance path for ground fault current.

Figure 8–15 illustrates a second method of grounding a three-phase, four-wire delta system with a high leg. In this case there is a separate service disconnect for three-phase power and a separate disconnect for the single-phase lighting. Here all four conductors are brought to a wireway or auxiliary gutter and the grounded conductor is connected to the grounding electrode conductor and carried into the power service equipment and into the lighting. This same system of connection could be used with a CT can, in which case the connections made in the CT can are like those made in the auxiliary gutter.

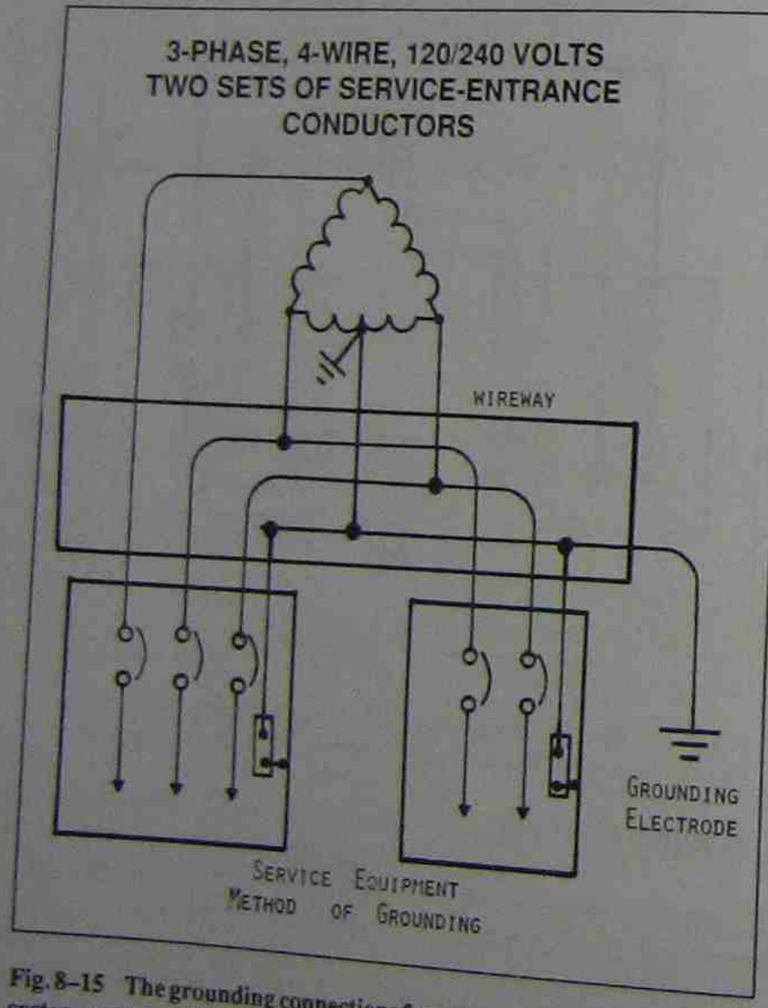

Fig. 8–15 The grounding connections for a three-phase, four-wire delta system are permitted to be made in a wireway.

MULTIPLE SERVICE DISCONNECTING MEANS

Figure 8–16 illustrates the use of more than one service disconnecting switch for one set of service-entrance conductors. One disconnect serves the 120/208-volt lighting load and two disconnecting switches serve the 208-volt, three-phase, power loads. The grounded conductor (the neutral) will be brought into the lighting switch and extended beyond the service disconnect switch for the lighting.

For the best installation, the grounded conductor will be brought into the power disconnecting switches, even though it will not extend beyond the service disconnecting switch. In case of a fault beyond the power switch, there will be a lower impedance path for the fault current than if the grounded conductor is not brought into the disconnect switch. When the raceway between the wireway and the service switches is nonmetallic, the grounded conductor shall be brought into the power switches.

When the grounded conductor is not brought into the power switches, and metal raceway is used between the wireway and the service switch, the metal raceway then becomes the fault current conductor, as illustrated in figure 8–17. This installation is allowed in some areas. These connections are on the line side of the service overcurrent protective device. Anything that can be done to ensure continuity and a low-impedance ground path on the line side of the service is an advantage.

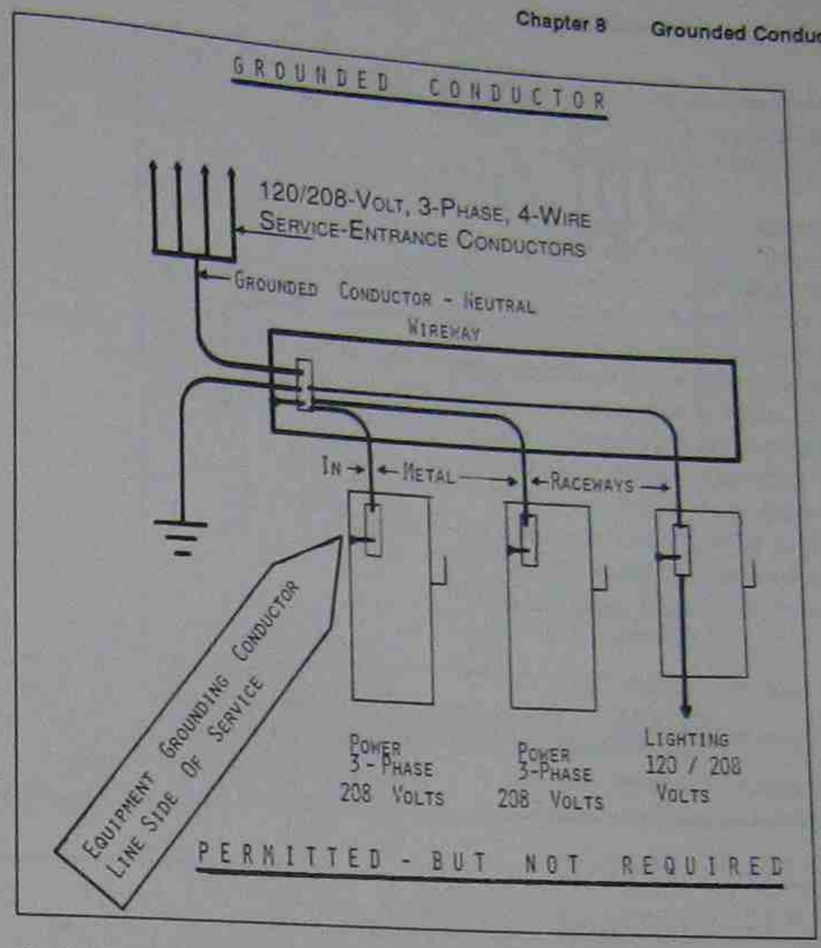

Fig. 8–16 A grounded conductor connection with more than one service disconnect switch.

SYSTEM OR CIRCUIT CONDUCTOR TO BE GROUNDED

Figure 8–18 illustrates the conductors that shall be grounded for the various systems listed in *Section 250-25* of the Code. The five systems are:

1. Single-phase, two-wire—one conductor is grounded.
2. Single-phase, three-wire—one conductor is grounded.
3. Multiphase system with one wire common to all phases—the common conductor is grounded.
4. Multiphase system with one phase grounded—one phase conductor is grounded.

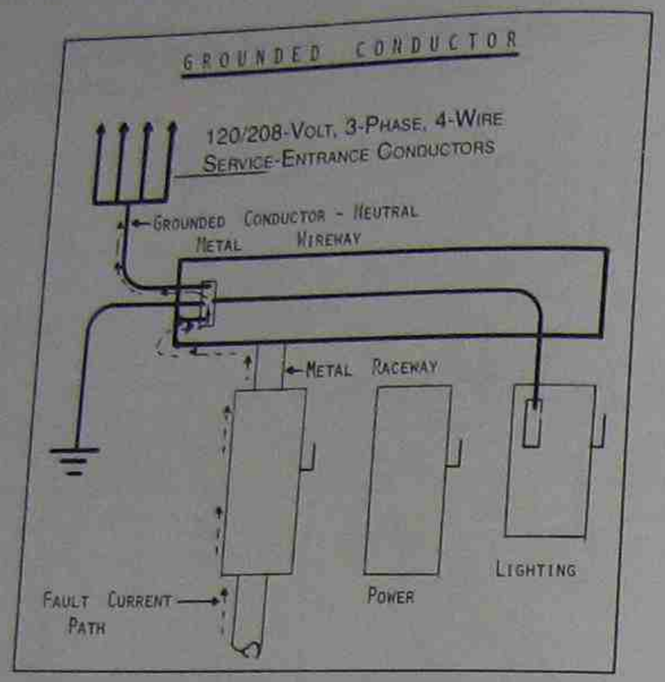

Fig. 8–17 The ground fault path when a grounded conductor connection is not made in the power switch.

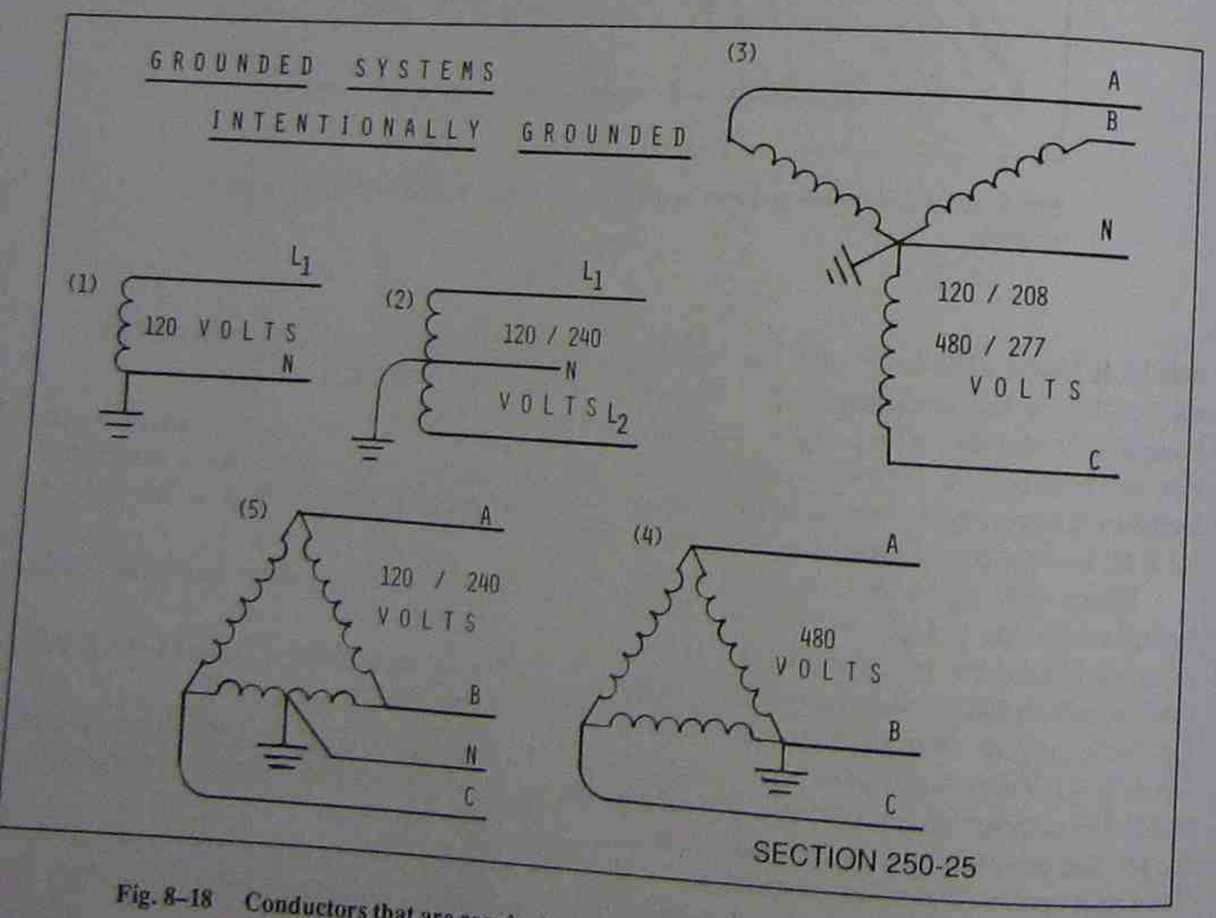

Fig. 8–18 Conductors that are required to be grounded, according to *Section 250-25*.

5. Multiphase system from which a single-phase, three-wire system is derived—the neutral conductor is grounded.

IDENTIFYING THE GROUNDED CONDUCTOR

Not all the information needed to identify the grounded conductor is in *Article 250*. Identification of the grounded conductor is made in *Article 200*, which dedicates the color white or natural gray to the grounded (neutral) conductor *(Section 200-7)*.

This section also prohibits a conductor with white or natural gray insulation from being used as an ungrounded conductor. However, there are a few exceptions.

Exception No. 1 permits an insulated conductor with a white outer finish to be used as an ungrounded circuit conductor when it is permanently reidentified to indicate its use, by painting or other effective means, at each location the conductor is visible and accessible. Figure 8–19 illustrates an insulated conductor with a white finish being used as the ungrounded conductor to supply a 240-volt, single-phase motor. The white conductor is reidentified at the panel and the motor.

Exception No. 2 permits an insulated conductor with a white or natural gray finish to be used for switch loops for single-pole, three-way, and four-way switches. Figure 8–20 illustrates the use of the insulated conductor with a white finish with a single-pole switch; figure 8–21 shows use with three- and four-way switches. When the white conductor is used as switch loops, it is not reidentified.

There are three recognized means for identifying a grounded conductor *(Section 200-6(a))* for No. 6 and smaller conductors (figure 8–22). The identification must extend the entire length of the conductor.

1. No. 6 and smaller—white or natural gray
2. Aerial cable—ridge on exterior of cable
3. An outer covering of white insulation with colored tracer threads permitted

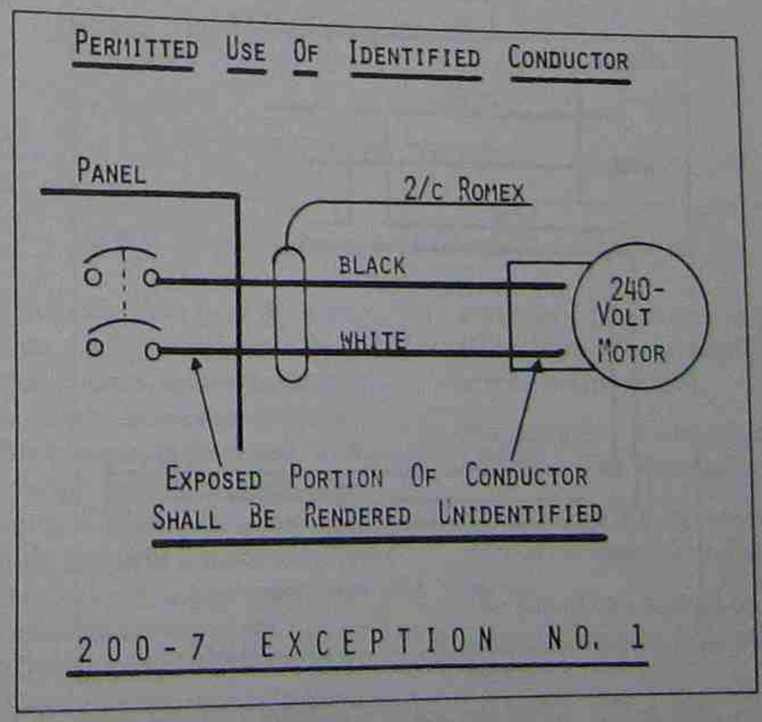

Fig. 8–19 An example of permitted use of a grounded conductor as an ungrounded conductor.

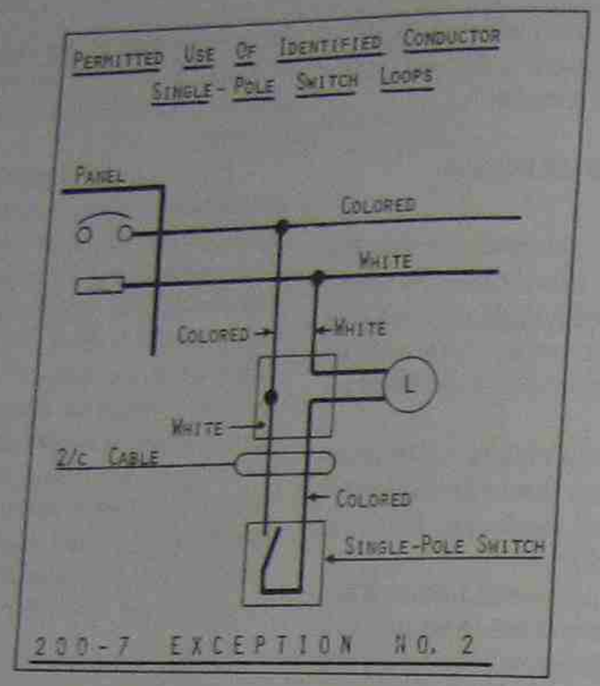

Fig. 8–20 Permitted use of a grounded conductor as an ungrounded conductor using a single-pole switch loop as an example.

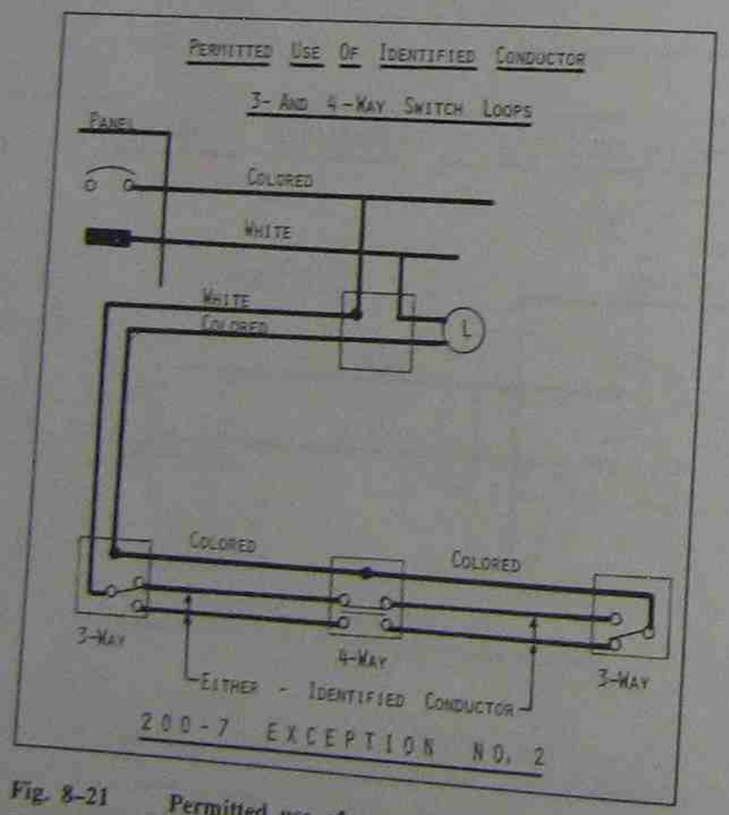

Fig. 8–21 Permitted use of a grounded conductor as an ungrounded conductor using three-way and four-way switch loops as an example.

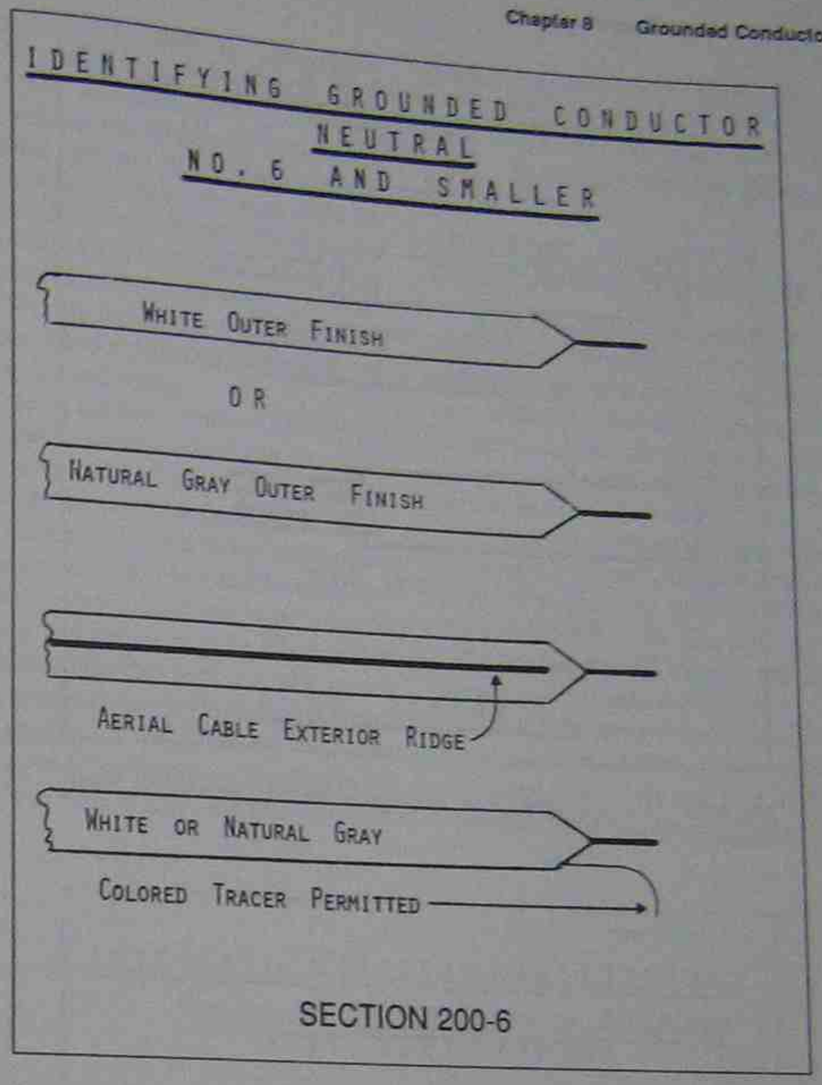

Fig. 8–22 Identifying a grounded conductor No. 6 and smaller.

There are five exceptions listed to the requirement that the conductor be white. These are some common-sense exceptions that have to do with special cable assemblies or special installations. For example, in Exception No. 5 (figure 8–23) when mineral-insulated cable (Type MI) is used, it does not have to have a white outer finish. But some distinctive marking shall be used to identify the grounded conductor at its terminations or exposures.

Section 200-6(a), Exception No. 4 permits a conductor without a white-colored insulation to be used as the grounded conductor, provided the following conditions are met:

1. Conditions of maintenance and su
sion assure that only qualified perso
service the installation.
2. The grounded conductor is perma
identified at its terminations.
3. Identification of the grounded condu
done at the time of installation.
4. The identification shall be by disti
white markings or other equally ef
means.

The basic requirement for identif
grounded conductor larger than No. 6

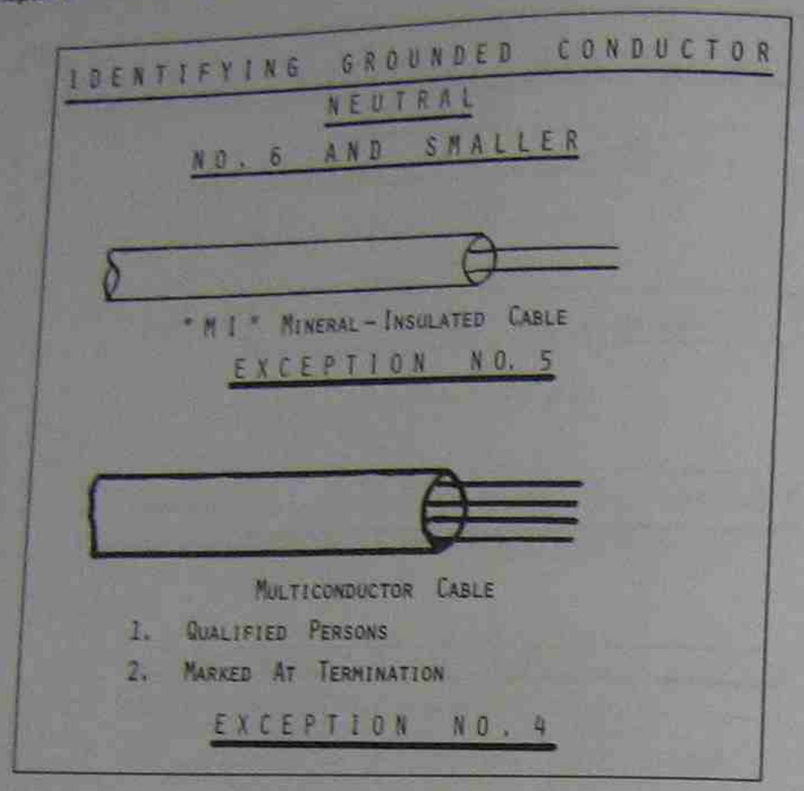

Fig. 8–23 Two exceptions to identifying a grounded conductor No. 6 and smaller.

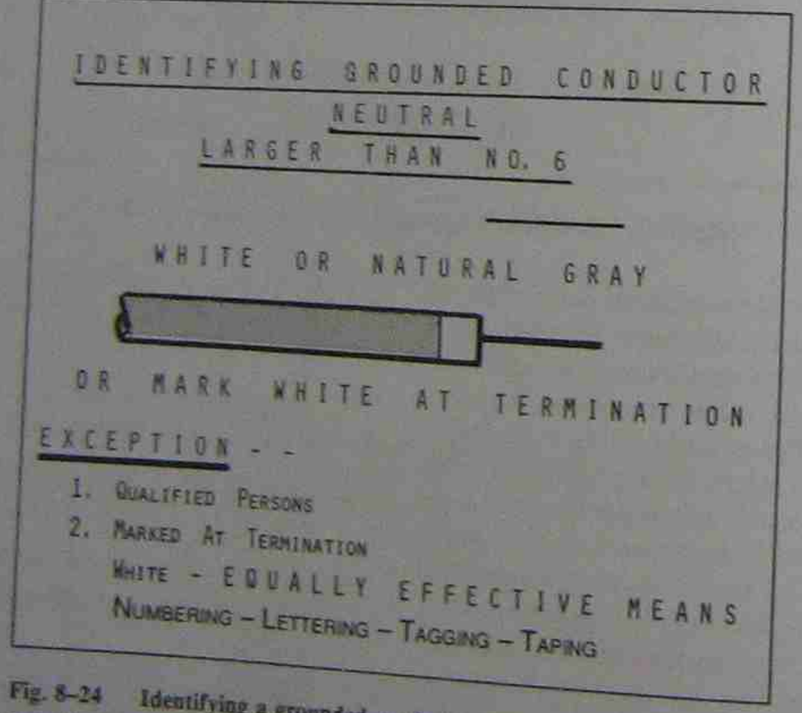

Fig. 8–24 Identifying a grounded conductor larger than No. 6. Includes exceptions to the requirement.

same as for the smaller conductor: it must have a white or natural gray outer finish (figure 8–24). The exception allows something other than white or natural gray to be used when only qualified persons will service it under proper maintenance and supervision. Then the grounded conductor must be identified by some means that will be as effective as the outer white finish. Some of the effective means permitted to be used to identify the grounded conductor at its terminations include painting, numbering, lettering, tagging, and taping.

The use of the color white to identify the grounded conductor of a branch circuit is covered in *Section 210-5 (Color Code for Branch Circuits)* and is illustrated in figure 8–25. It considers the installation of two different grounded systems in the same raceway and then requires the grounded conductor of one to be white or natural gray and the other to be white with a colored tracer (other than green) or other means of identification on the outside of the conductor. As an example, a 277/480-volt, four-wire grounded system for lighting is installed in the same raceway with a 120/240-volt, three-wire grounded system for receptacles. There will be two neutrals installed. One neutral will be either white or gray and the second neutral could be white with a stripe, other than green.

GROUNDED CONDUCTOR OVERCURRENT PROTECTION

Figure 8–26 (a) illustrates the use of a fuse as an overcurrent protective device connected in series with a neutral conductor. This is a violation of *Section 240-22*; it prohibits using an overcurrent device in series with an intentionally grounded conductor. This means no overcurrent device in the neutral.

However, there are a couple of exceptions. The first is illustrated in figure 8–26 (b), where a circuit breaker will open the neutral and all other conductors at the same time and is permitted to be used as an overcurrent device connected in series with the neutral.

A circuit breaker with a handle tie would not be permitted, because it is possible for such a breaker to trip only one pole of the breaker. However, there are some circuit breakers on the

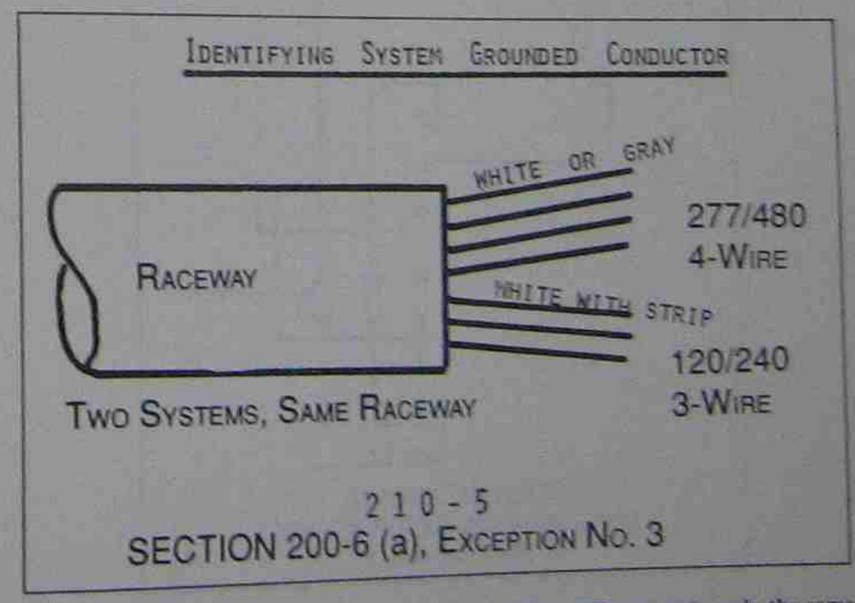

Fig. 8–25 Identifying the grounded conductor of two different systems in the same raceway.

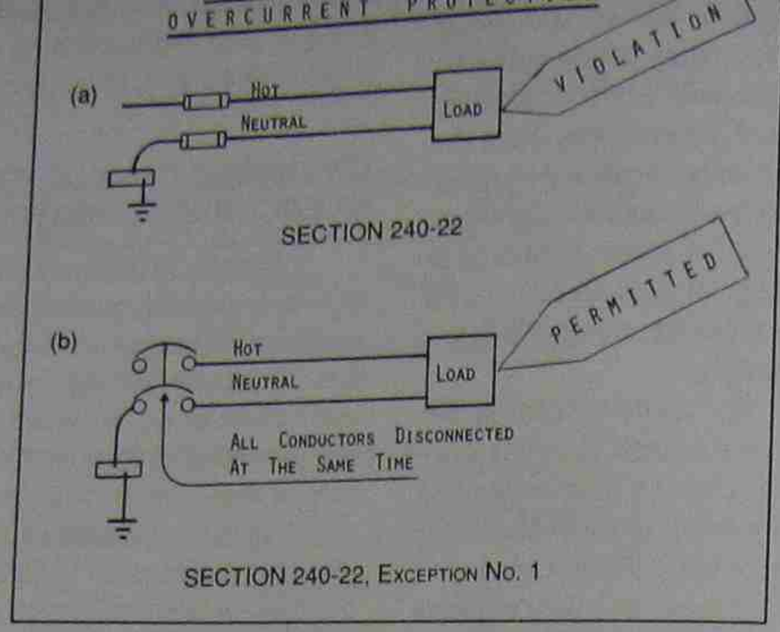

Fig. 8–26 (a) A violation of the grounded conductor overcurrent protection rule; (b) an example of overcurrent protection permitted by an exception.

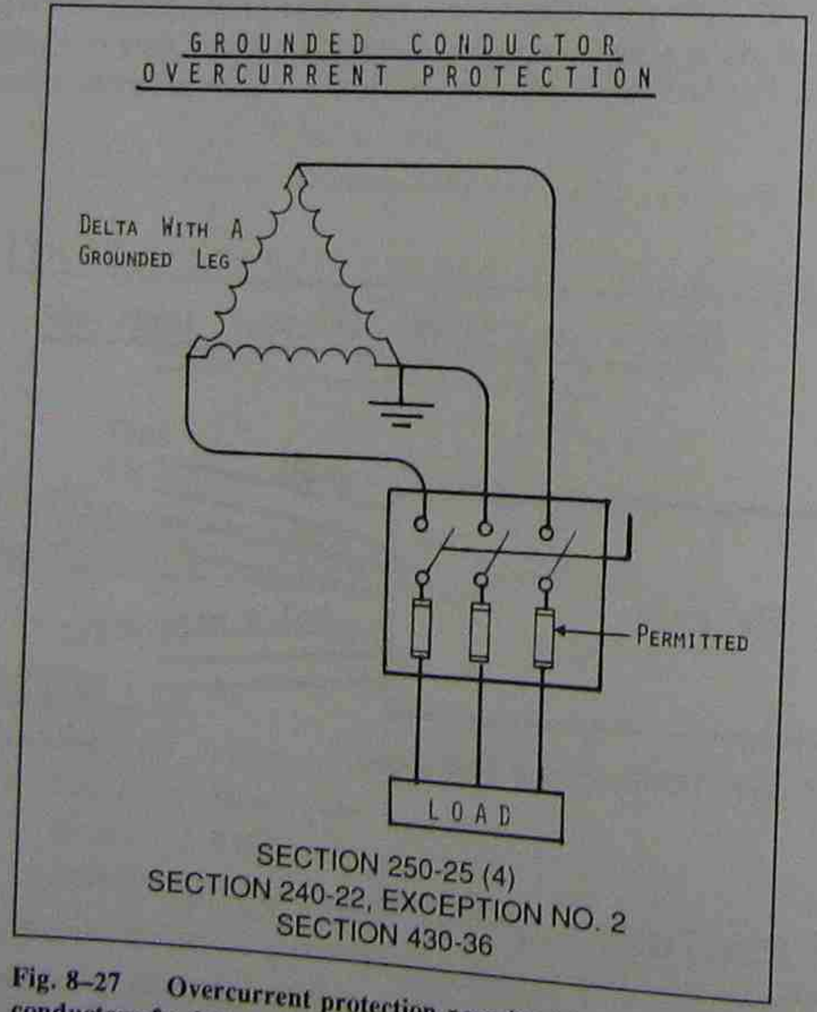

Fig. 8–27 Overcurrent protection permitted in the grounded conductor of a delta-connected system with a grounded leg.

market that will trip all poles when they are connected with a handle tie. Fuses do not trip all poles. The exception requires all poles to be opened by the overcurrent protective device.

Exception No. 2 is illustrated in fig-

CHAPTER 9

Main Bonding Jumper

This chapter focuses on the main bonding jumper (figure 9–1). Covered are its purpose, its location in the ground path, the materials used, connections, and sizing. The main bonding jumper is a very important link in the overall grounding system. Information presented in *Article 250* for the main bonding jumper is also coordinated in *Section 384-3(c)*, which discusses switchboards and panels used as service equipment.

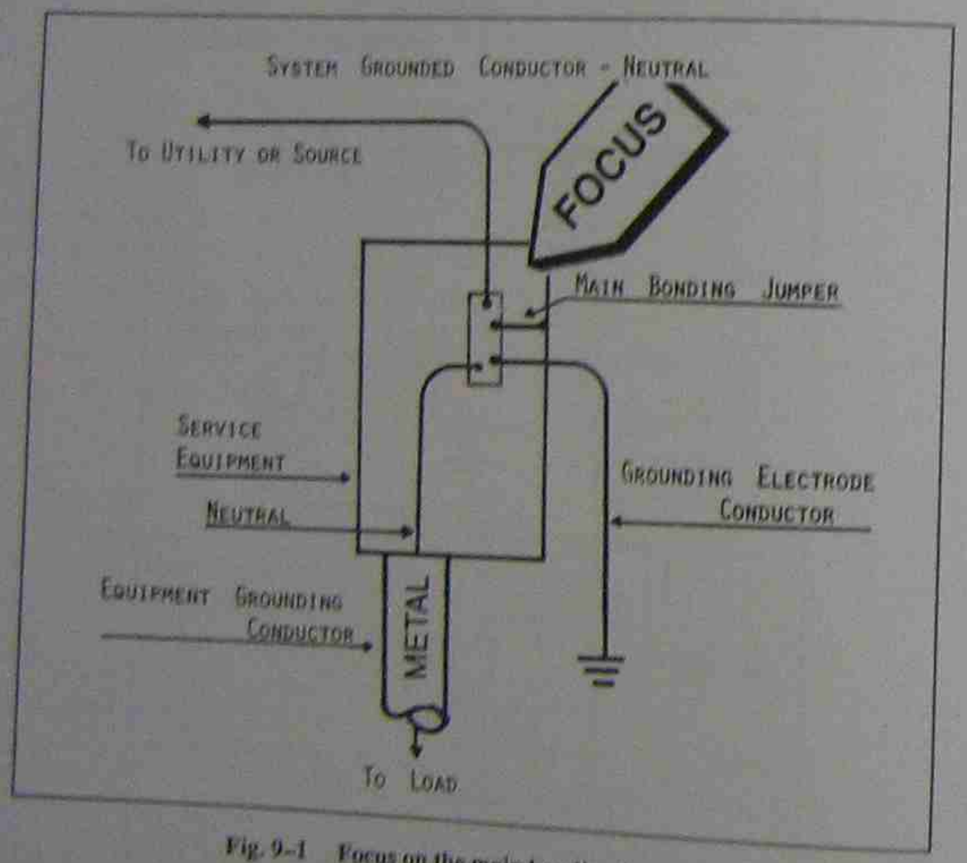

Fig. 9–1 Focus on the main bonding jumper.

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DEFINITION OF *MAIN BONDING JUMPER*

Article 100 defines the main bonding jumper as follows (figure 9–2):

Quote – "The connection between the grounded circuit conductor and the equipment grounding conductor at the service."*

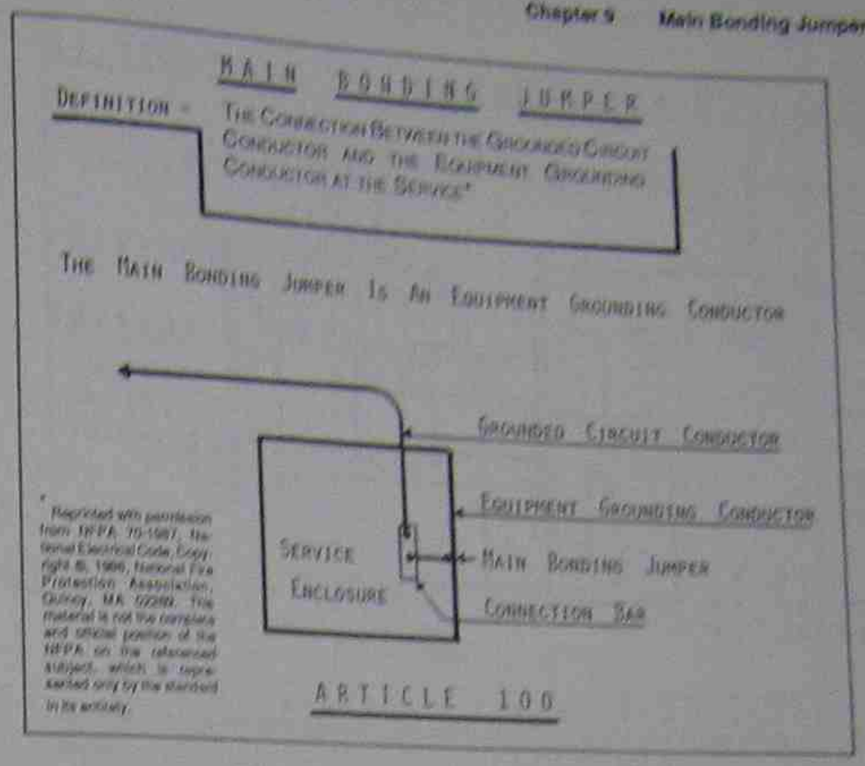

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Fig. 9–2 Definition of *main bonding jumper*.

Comment: This definition makes two very important points. These are:

1. Two specific conductors are connected together.
2. The connection is made at the service.

As illustrated earlier (chapter 4, figure 4–9), under fault conditions, the grounded circuit conductor becomes the equipment grounding conductor, through the main bonding jumper.

Although it is not specifically stated in the definition, there is another important connection the main bonding jumper makes. When the metal enclosures and metal raceways are used for the equipment grounding conductor, the main bonding jumper is in series with the grounding electrode conductor and connects the equipment grounding conductor to the grounding electrode system. This connection, required by *Section 250-23(b)*, provides the zero-to-ground potential for equipment connected to the equipment grounding conductor.

Comment: Note the use of the terminology "grounded circuit conductor" in the definition. This means there is no main bonding jumper for an ungrounded system. For example, a three-phase, three-wire, 480-volt wye connected system would have no grounded conductor and no main bonding jumper. However, it would have an equipment bonding jumper.

When the metal equipment enclosures and metal raceways are used as the equipment grounding conductor, the main bonding jumper is the direct link to the system grounded conductor and the grounding electrode system. When the main bonding jumper is left out, it is the missing link, creating an open circuit and an invitation to a dangerous situation.

LOCATION OF THE MAIN BONDING JUMPER

As illustrated in figure 9–3, the main bonding jumper is installed at the service, in the service equipment. It is considered to be on the

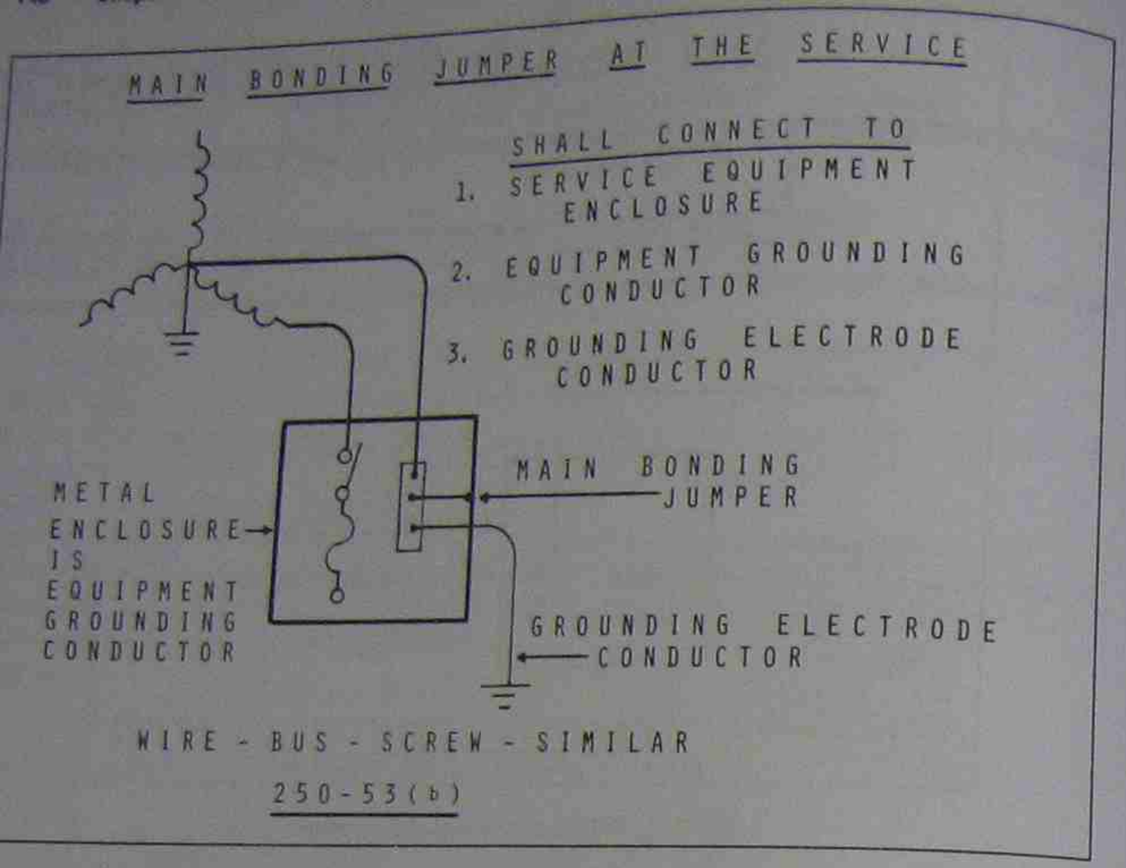

Fig. 9–3 Installation of the main bonding jumper at the service.

side of the service equipment. It can be lo-
d in the service equipment or in any of the
ice equipment enclosures.

Section 250-53(b) contains a lot of regula-
applying to the main bonding jumper.
e include:

The main bonding jumper is used only with grounded systems.

The main bonding jumper shall be unspli-ced.

Comment: Note how this section mentions grounded system," just as the definition in *e 100* did. Also, there are no exceptions for splicing the main bonding jumper.

he purpose of the main bonding jumper is connect the equipment grounding con-uctor to the grounded conductor.

ne connection shall be made within the rvice equipment.

5. It is also permitted to be made within the service conductor enclosures, such as a current transformer (CT) can or auxiliary gutter.

Figure 9–3 illustrates connecting all of these grounding conductors together within the service equipment.

Comment: Once again the Code focuses on the bull's eye target of grounding by connecting the four key grounding conductors—

- the grounded conductor
- the equipment grounding conductor
- the grounding electrode conductor
- the main bonding jumper

all together at the service.

Item 5, listed above, allows the main bonding jumper to be installed in the CT can, as illustrated in figure 9–4, or in a metal wireway used for service-entrance conductors, as illustrated in figure 9–5.

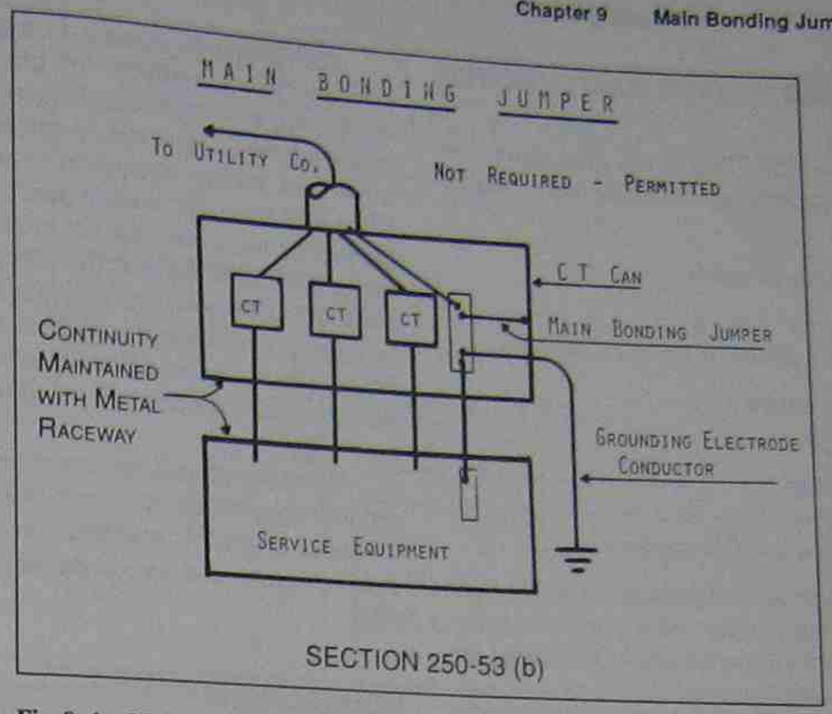

Fig. 9–4 Main bonding jumper connection permitted in CT can ahead of service switch.

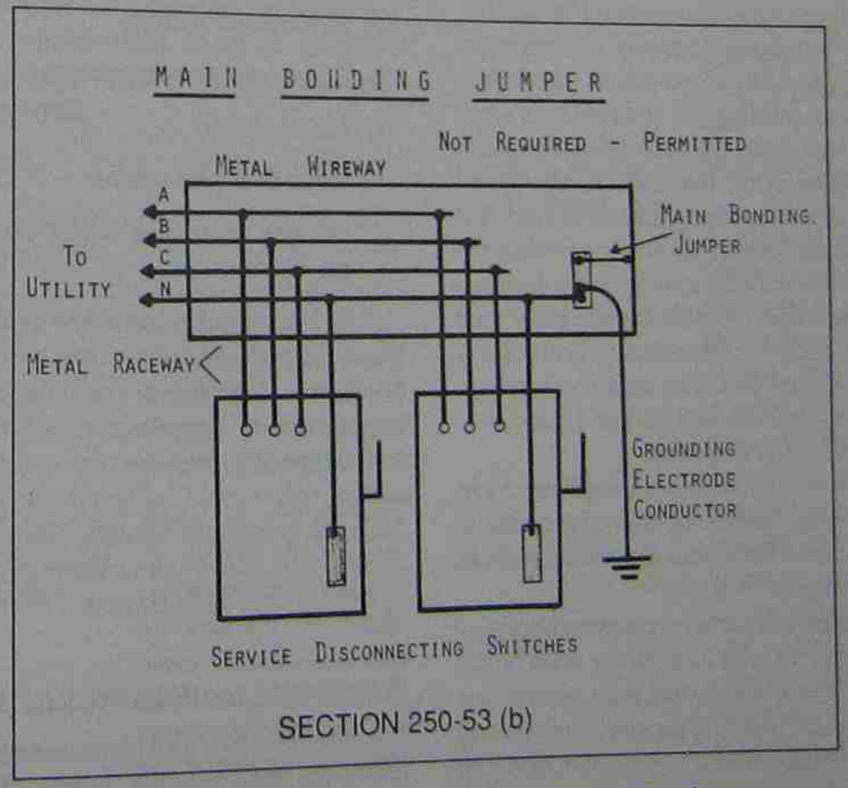

Fig. 9–5 Main bonding jumper connection permitted in wireway.

TERIALS FOR THE MAIN BONDING MPER

Section 250-79(a) gives information on t materials can be used for the main bonding er.

The material can be

a. copper
b. other corrosion-resistant material

t is permitted to be

. wire
. bus bar
. screw
. similar suitable conductor

omment: Although copper is specifically ned, the phrase "other corrosion-resis- terials" allows the use of aluminum for in bonding jumper.

group of electrical inspectors was asked stion, What one Code rule do you find olated? The answer was, The screw for n bonding jumper in the service switch is erly installed or not used when making ntial or small commercial installation. en equipment is approved for service nt, there will be provisions for the main jumper. Often it is a screw that, when d, will make contact with the metal e. However, the service equipment always come with this screw grounded etal enclosure. By not grounding the closure at the factory, it makes the piece nent more versatile for use other than e equipment. Therefore, it is necessary lectrician to make sure the screw is ll the way in and makes a good con- the metal enclosure.

screw is the Main Bonding Jumper and nportant part in the overall grounding. n important link in the ground path, as in figure 9–6.

large service where a switchboard is a screw is not used as the main bond- r. The switchboard may or may not a main bonding jumper installed. It is to make sure that the main bonding here and is installed properly.

CAUTION: Equipment is manufactured with the screw available for grounding the equipment, thereby making it approved for service equipment. However, it can be used for other than service equipment. For example, when used for a distribution panel, other than the service, the screw must not be grounded. In this case it is safer to discard the screw so that no one looks at the panel, possibly thinks it should be making a connection, and screws the screw down. This is explained and illustrated in the next chapter, "Equipment Grounding Conductor."

When the ground bus is connected to the service enclosure, the entire enclosure becomes a conductor with a considerable amount of cross-sectional area for conducting fault current.

CONNECTIONS

Section 250-113 covers the methods permitted for connecting the main bonding jumper. The connection is permitted to be made by any of the following:

1. Exothermic welding
2. Listed pressure connectors
3. Listed clamps
4. Other approved means
5. Devices depending solely on solder not permitted

Reason: Solder has a low melting point. When there is a very high fault current, heat is developed. Enough heat could be generated to melt the solder. Depending on the position of the solder-type lug used for the connection, the melting solder could easily run out of the lug and cause the grounding circuit to open. The solder also may be blown out of the lug by magnetic motor action of fault current.

SIZING THE MAIN BONDING JUMPER

Section 250-79(c) gives three methods for sizing the main bonding jumper. When sizing the main bonding jumper, the size and material of the service-entrance conductors and the material used for the main bonding conductor are taken into consideration. Each of the three methods and some variations of the three methods are illustrated.

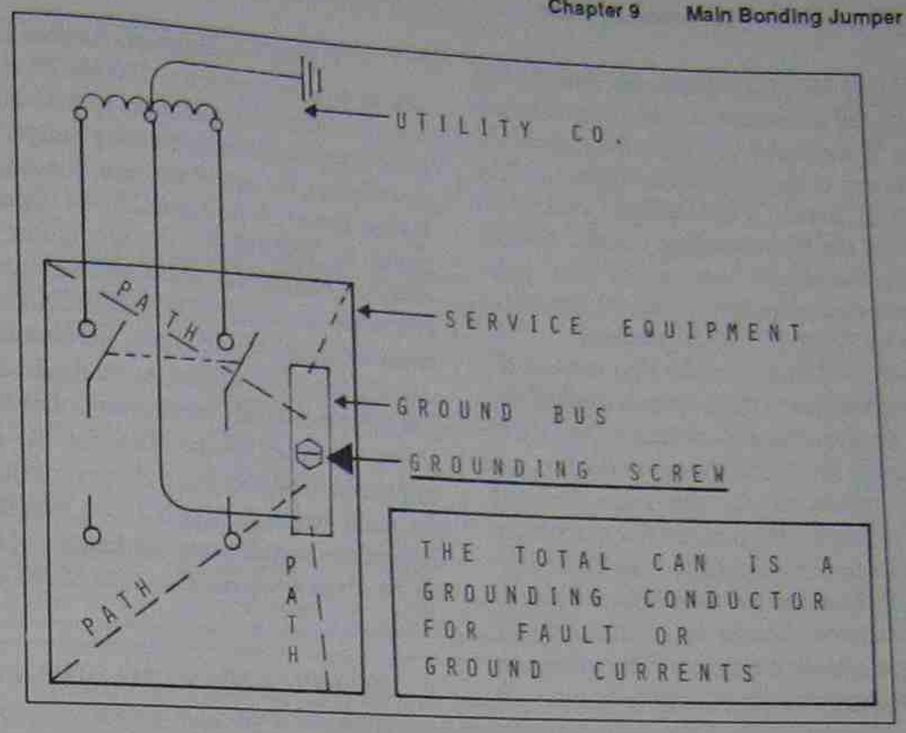

Fig. 9–6 Total metal enclosure, including grounding screw, is equipment grounding conductor to main bonding jumper.

Method	Requirement
1. Basic Rule: Use *Table 250-94*	*Table 250-94* the Grounding Electrode Conductor table, is also used for sizing the Main Bonding Jumper, which is required to be not smaller than the size given in *Table 250-94*.
2. 12-1/2 Percent Rule for Large Conductors	When the total circular-mil area of any service-entrance phase conductor exceeds the maximum circular-mil area listed in *Table 250-94* (1100 MCM for copper and 1750 CM for aluminum), the main bonding jumper shall not be smaller than 12-1/2 percent of the service-entrance phase conductors.
3. Rule for Using Different Materials	This rule applies when the Main Bonding Jumper is a different material than the service-entrance conductors. One could be aluminum and the other copper, for example. In this case, the minimum size of the main bonding jumper is based on assuming that the service-entrance conductors are of the same material as the main bonding jumper and that the ampacity is equivalent to the installed phase conductors.

CAUTION: Take particular note that in method 1, the same table is used to size the main bonding jumper and the grounding electrode conductor up to the maximum size listed in the table, even though *Table 250-94* makes no mention of the main bonding jumper. Also in method 1, the phrase "not smaller than" indicates that a conductor larger than the conductor required by *Table 250-94* is permitted.

Figure 9–7 illustrates the first method for calculating the size of the main bonding jumper. It shows the use of single conductor, 500 MCM copper for the service-entrance conductors and copper conductor for the main bonding jumper. For this installation, the size of the main bonding jumper is read directly from *Table 250-94* (figure 9–8) under the heading for the copper service-entrance conductors and copper grounding electrode conductor. The minimum size of the main bonding jumper is No. 1/0 copper.

Figure 9–9 illustrates method 1 with the use of single-conductor, 500 MCM aluminum service-entrance conductors and an aluminum conductor for the main bonding jumper. For this installation, the size of the main bonding jumper is read directly from *Table 250-94* (figure 9–10) under the heading for the aluminum service-entrance conductors and aluminum grounding electrode conductor. The minimum size of the main bonding jumper is No. 1/0 aluminum.

Figure 9–11 illustrates method 1 with the use of two 500 MCM copper conductors per phase, connected in parallel, for the service-entrance conductors and a copper conductor for the main bonding jumper. The parallel conductors are treated as one conductor and the total MCM of the two paralleled 500 MCM conductors is:

500 MCM + 500 MCM = 1000 MCM per phase

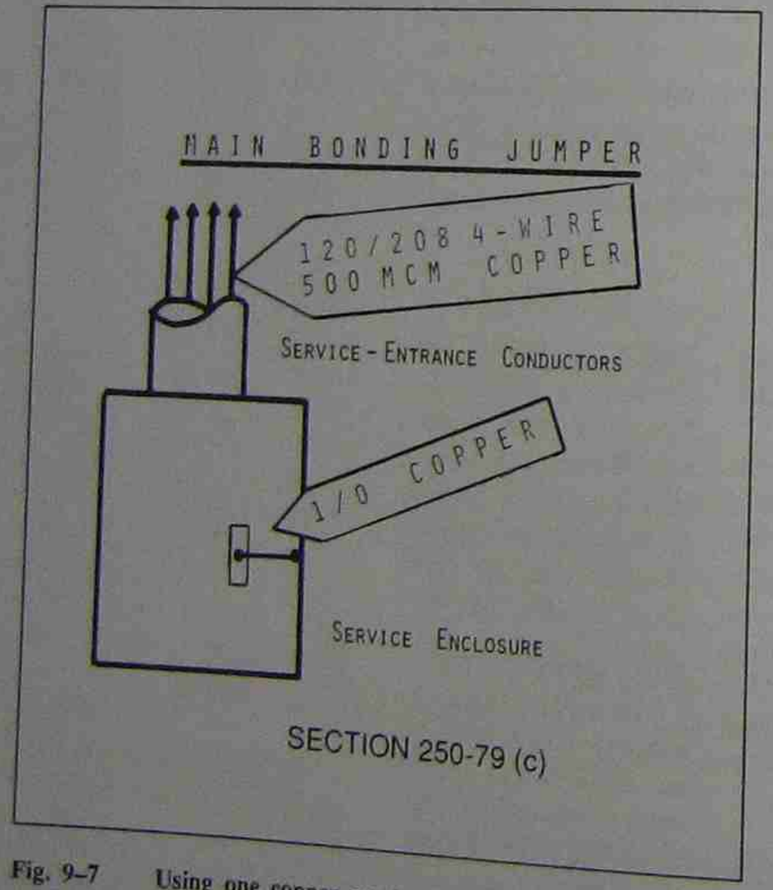

Fig. 9–7 Using one copper conductor per phase as the service conductors for a grounded AC system with a copper main bonding jumper.

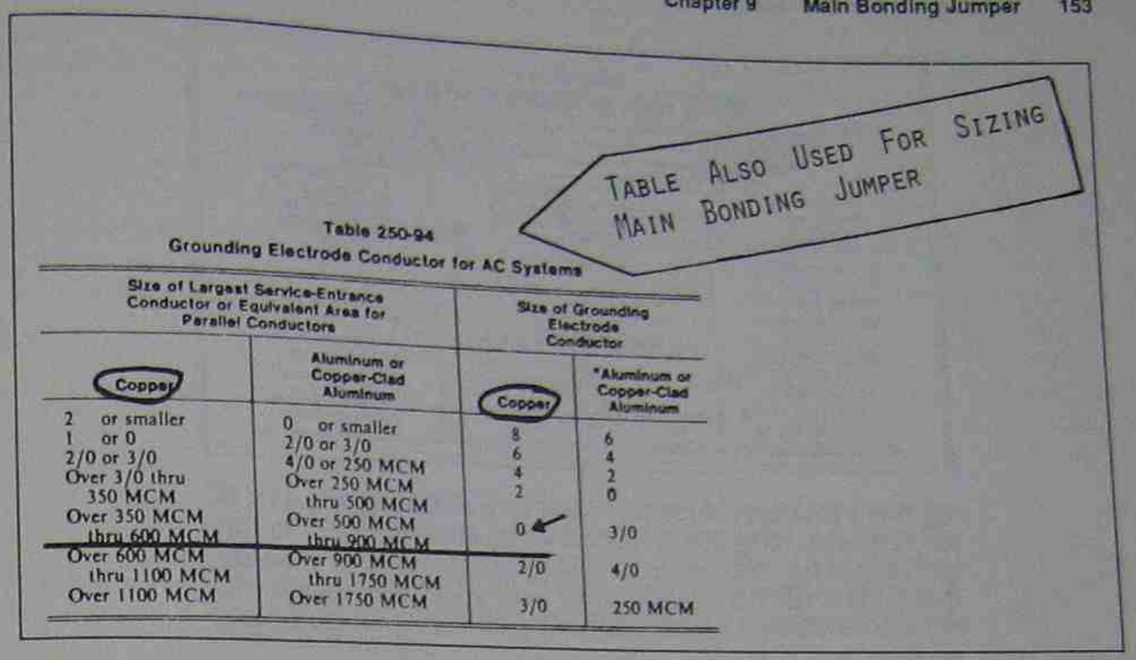

Table 250-94
Grounding Electrode Conductor for AC Systems

Size of Largest Service-Entrance Conductor or Equivalent Area for Parallel Conductors		Size of Grounding Electrode Conductor	
Copper	Aluminum or Copper-Clad Aluminum	Copper	*Aluminum or Copper-Clad Aluminum
2 or smaller	0 or smaller	8	6
1 or 0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250 MCM	4	2
Over 3/0 thru 350 MCM	Over 250 MCM thru 500 MCM	2	0
Over 350 MCM thru 600 MCM	Over 500 MCM thru 900 MCM	0	3/0
Over 600 MCM thru 1100 MCM	Over 900 MCM thru 1750 MCM	2/0	4/0
Over 1100 MCM	Over 1750 MCM	3/0	250 MCM

Fig. 9–8 **Reading *Table 250-94* for sizing the main bonding jumper for the service illustrated in figure 9–7.** Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright ©, 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

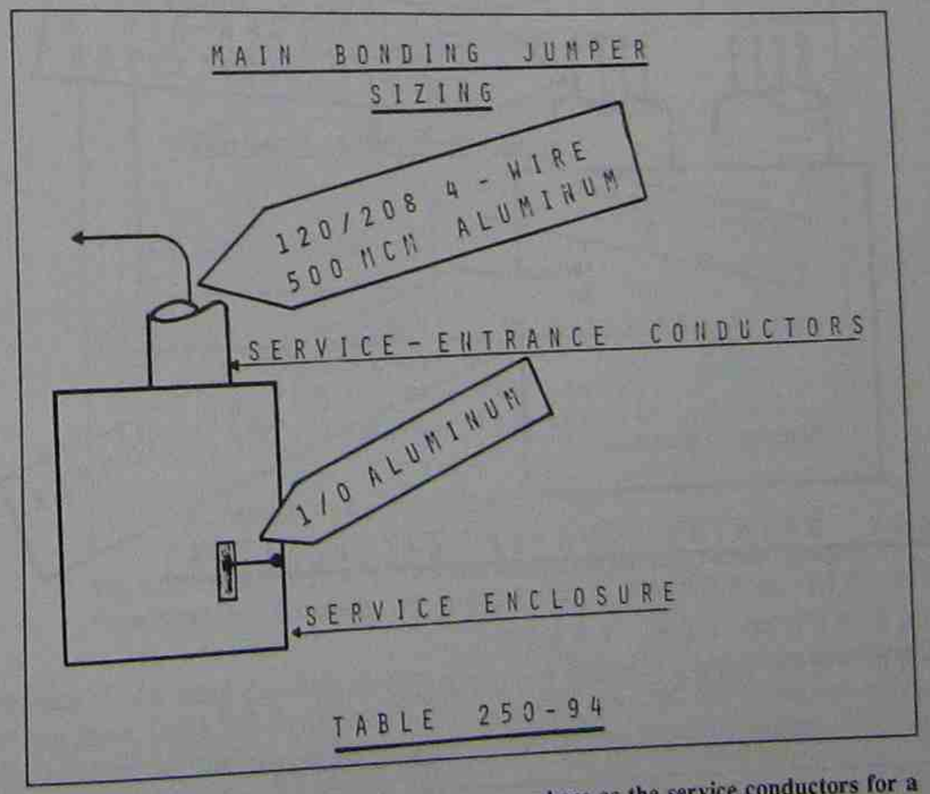

Fig. 9–9 **Using one aluminum conductor per phase as the service conductors for a grounded AC system with a copper main bonding jumper.**

Table 250-94
Grounding Electrode Conductor for AC Systems

Size of Largest Service-Entrance Conductor or Equivalent Area for Parallel Conductors		Size of Grounding Electrode Conductor	
Copper	Aluminum or Copper-Clad Aluminum	Copper	*Aluminum or Copper-Clad Aluminum
2 or smaller	0 or smaller	8	6
1 or 0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250 MCM	4	2
Over 3/0 thru 350 MCM	Over 250 MCM thru 500 MCM	2	0
Over 350 MCM thru 600 MCM	Over 500 MCM thru 900 MCM	0	3/0
Over 600 MCM thru 1100 MCM	Over 900 MCM thru 1750 MCM	2/0	4/0
Over 1100 MCM	Over 1750 MCM	3/0	250 MCM

Fig. 9–10 Reading *Table 250-94* for sizing the main bonding jumper for the service illustrated in figure 9–9. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright © 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

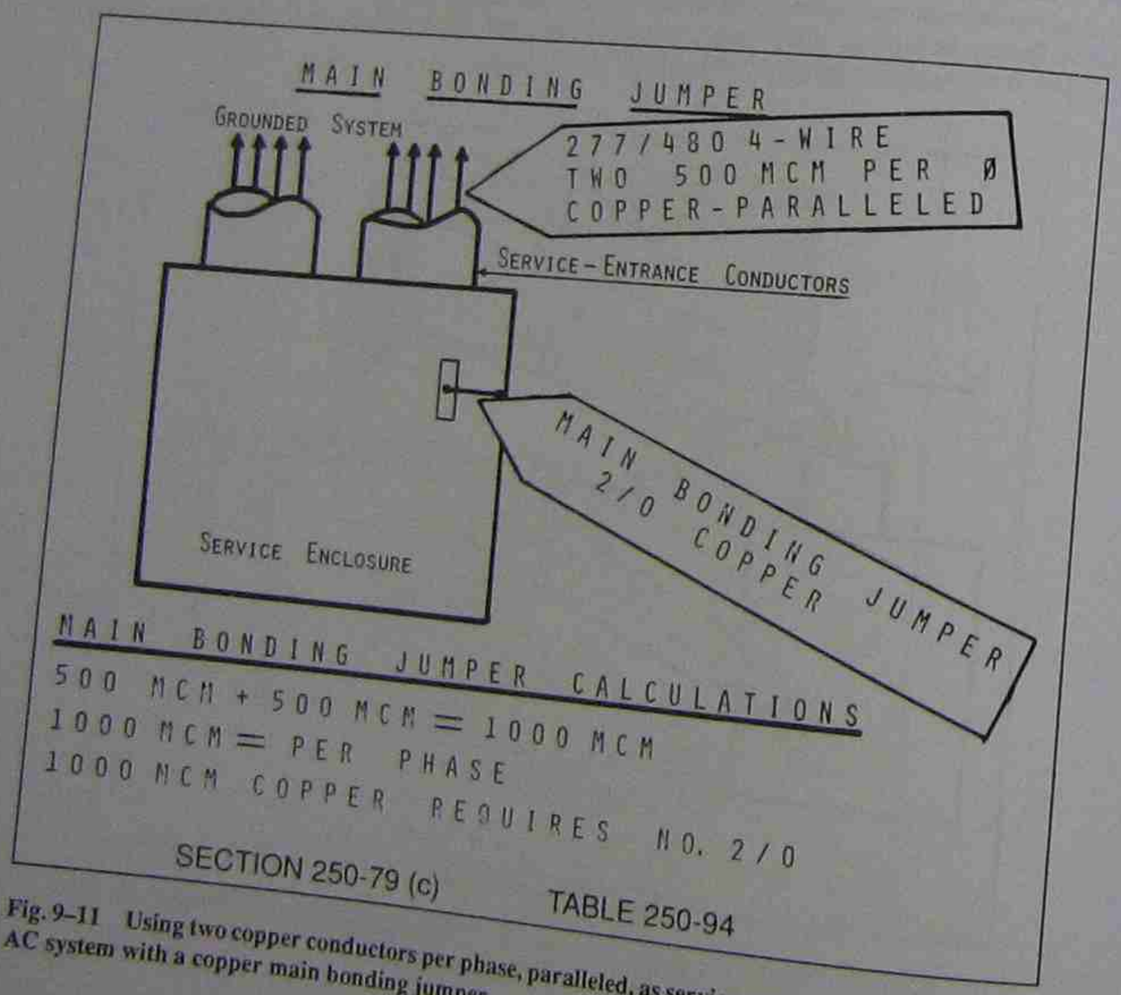

Fig. 9–11 Using two copper conductors per phase, paralleled, as service conductors for a grounded AC system with a copper main bonding jumper.

Table 250-94
Grounding Electrode Conductor for AC Systems

Size of Largest Service-Entrance Conductor or Equivalent Area for Parallel Conductors		Size of Grounding Electrode Conductor	
Copper	Aluminum or Copper-Clad Aluminum	Copper	*Aluminum or Copper-Clad Aluminum
2 or smaller	0 or smaller	8	6
1 or 0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250 MCM	4	2
Over 3/0 thru 350 MCM	Over 250 MCM thru 500 MCM	2	0
Over 350 MCM thru 600 MCM	Over 500 MCM thru 900 MCM	0	3/0
Over 600 MCM thru 1100 MCM	Over 900 MCM thru 1750 MCM	2/0	4/0
Over 1100 MCM	Over 1750 MCM	3/0	250 MCM

Fig. 9–12 Reading *Table 250-94* for sizing the main bonding jumper for the service illustrated in figure 9–11. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright © 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

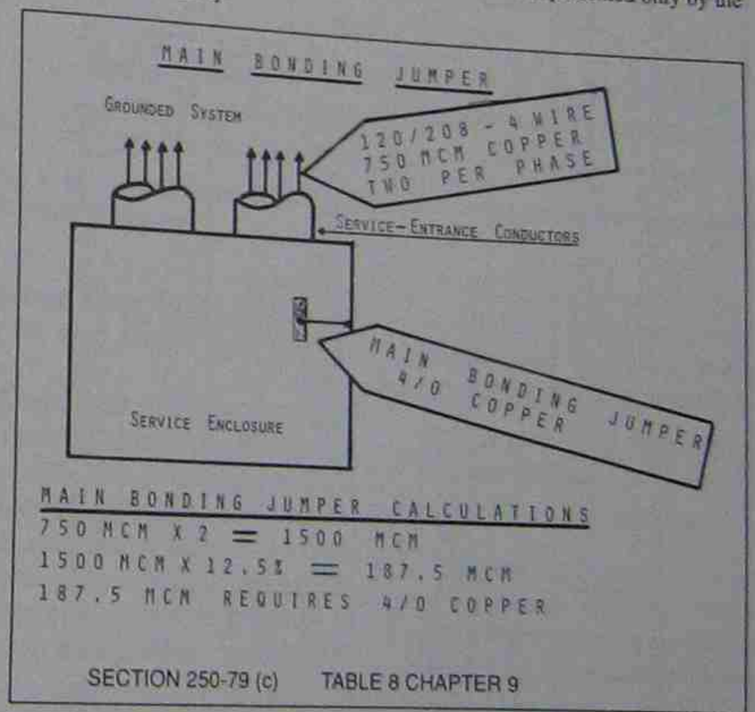

Fig. 9–13 Using the 12-1/2 percent rule to size a copper main bonding jumper for a grounded AC system.

The size of the main bonding jumper is read directly from *Table 250-94* (figure 9–12) under the heading for the copper service-entrance conductors and copper grounding electrode conductor. The minimum size of the main bonding jumper is No. 2/0.

Figure 9–13 illustrates method 2 use of two 750 MCM copper conduc phase, connected in parallel:

750 MCM + 750 MCM = 1500 M phase

This is larger than the 1100 MCM maximum listed in *Table 250-94*. Therefore, the 12-1/2 percent rule shall be used.

1500 MCM × 12-1/2% = 187.5 MCM or 187,500 circular mils

Table 8 (Chapter 9) *Conductor Properties* (figure 9–14) is used to convert the calculated circular-mil area into a standard wire size. In this case it is a little less than No. 4/0 but a little more than No. 3/0; therefore, the No. 4/0 must be used. The minimum size main bonding jumper required for this service is No. 4/0.

Question: Is the main bonding jumper ever required to be larger than the grounding electrode conductor?

Answer: Yes. Figure 9–15 illustrates the use of a ground rod for the grounding electrode. Because of an exception, a No. 6 copper conductor is permitted to be installed as the grounding

187500 CIRCULAR MILLS - 4/0

70–728 NATIONAL ELECTRICAL CODE

Table 8. Conductor Properties

Size AWG/MCM	Area Cir. Mils	Conductors: Stranding Quantity	Conductors: Stranding Diam. In.	Conductors: Overall Diam. In.	Conductors: Overall Area In.²	DC Resistance at 75°C (167°F): Copper Uncoated ohm/MFT	DC Resistance at 75°C (167°F): Copper Coated ohm/MFT	DC Resistance at 75°C (167°F): Aluminum ohm/MFT
18	1620	1	—	0.040	0.001	7.77	8.08	12.8
18	1620	7	0.015	0.046	0.002	7.95	8.45	13.1
16	2580	1	—	0.051	0.002	4.89	5.08	8.05
16	2580	7	0.019	0.058	0.003	4.99	5.29	8.21
14	4110	1	—	0.064	0.003	3.07	3.19	5.06
14	4110	7	0.024	0.073	0.004	3.14	3.26	5.17
12	6530	1	—	0.081	0.005	1.93	2.01	3.18
12	6530	7	0.030	0.092	0.006	1.98	2.05	3.25
10	10380	1	—	0.102	0.008	1.21	1.26	2.00
10	10380	7	0.038	0.116	0.011	1.24	1.29	2.04
8	16510	1	—	0.128	0.013	0.764	0.786	1.26
8	16510	7	0.049	0.146	0.017	0.778	0.809	1.28
6	26240	7	0.061	0.184	0.027	0.491	0.510	0.808
4	41740	7	0.077	0.232	0.042	0.308	0.321	0.508
3	52620	7	0.087	0.260	0.053	0.245	0.254	0.403
2	66360	7	0.097	0.292	0.067	0.194	0.201	0.319
1	83690	19	0.066	0.332	0.087	0.154	0.160	0.253
1/0	105600	19	0.074	0.373	0.109	0.122	0.127	0.201
2/0	133100	19	0.084	0.419	0.138	0.0967	0.101	0.159
3/0	167800	19	0.094	0.470	0.173	0.0766	0.0797	0.126
4/0	211600	19	0.106	0.528	0.219	0.0608	0.0626	0.100
250	—	37	0.082	0.575	0.260	0.0515	0.0535	0.0847
300	—	37	0.090	0.630	0.312	0.0429	0.0446	0.0707
350	—	37	0.097	0.681	0.364	0.0367	0.0382	0.0605
400	—	37	0.104	0.728	0.416	0.0321	0.0331	0.0529
500	—	37	0.116	0.813	0.519	0.0258	0.0265	0.0424
600	—	61	0.992	0.893	0.626	0.0214	0.0223	0.0353
700	—	61	0.107	0.964	0.730	0.0184	0.0189	0.0303
750	—	61	0.111	0.998	0.782	0.0171	0.0176	0.0282
800	—	61	0.114	1.03	0.834	0.0161	0.0166	0.0265
900	—	61	0.122	1.09	0.940	0.0143	0.0147	0.0235
1000	—	61	0.128	1.15	1.04	0.0129	0.0132	0.0212
1250	—	91	0.117	1.29	1.30	0.0103	0.0106	0.0169
1500	—	91	0.128	1.41	1.57	0.00858	0.00883	0.0141
1750	—	127	0.117	1.52	1.83	0.00735	0.00756	0.0121
2000	—	127	0.126	1.63	2.09	0.00643	0.00662	0.0106

Fig. 9–14 Using *Table 8* (Chapter 9) to convert circular mils to a numbered wire size. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright © 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

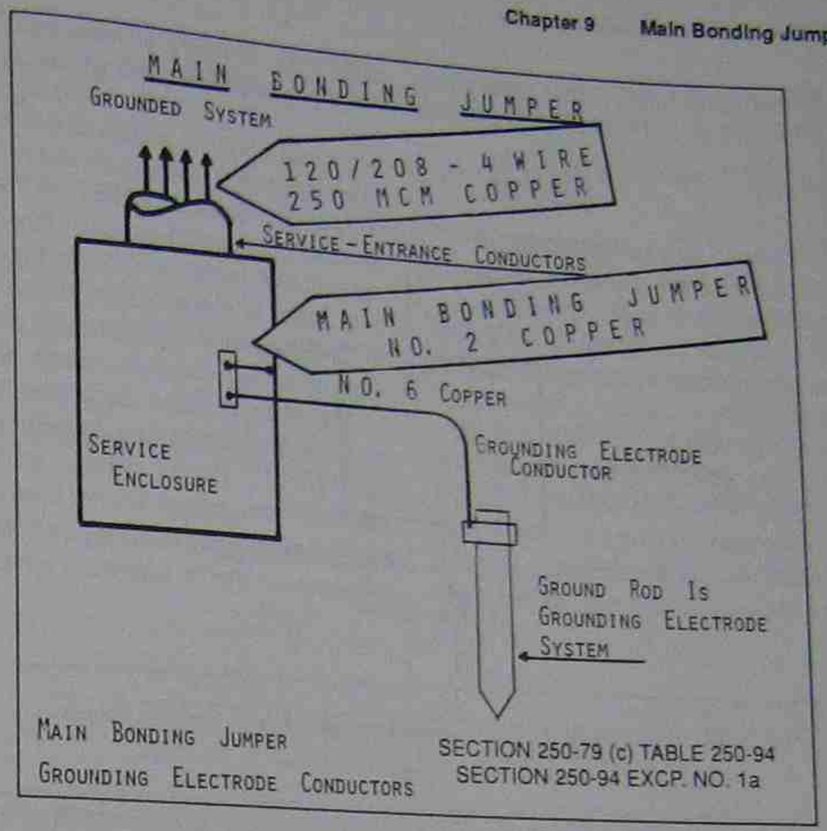

Fig. 9–15 Comparing the size of the main bonding jumper to the grounding electrode conductor.

electrode conductor. *Table 250-94* requires that No. 2 copper be used for the main bonding jumper.

Reason: Under fault conditions where the equipment grounding conductor consists of metal enclosures for electrical equipment and electrical conductors, such as a steel conduit installation, the main bonding jumper is required to carry the total fault current to the system grounded conductor for the quick operation of the overcurrent protective device, as illustrated in figure 9–16.

Note the following in figure 9–16:

1. Under fault conditions the metal raceway and metal enclosure are the equipment grounding conductors.
2. Watch the electron flow under fault conditions.
3. The electrons travel on the main bonding jumper.
4. Under fault conditions the system grounded conductor becomes an equipment grounding conductor.
5. The path of the fault current is channelled back through the overcurrent protective device.

Figure 9–17 gives a second example where the grounding electrode conductor will be smaller than the main bonding jumper. When using the 12-1/2 percent rule, the required main bonding jumper is 250 MCM. The grounding electrode conductor is read directly from *Table 250-94*. The 1800 MCM per phase is over the maximum 1100 MCM listed. It needs to be at least No. 3/0 copper, although it is not required to be larger than that.

It is not unusual for an installation to utilize aluminum service-entrance conductors and a copper main bonding jumper. Two different materials have been used and the ampacity of

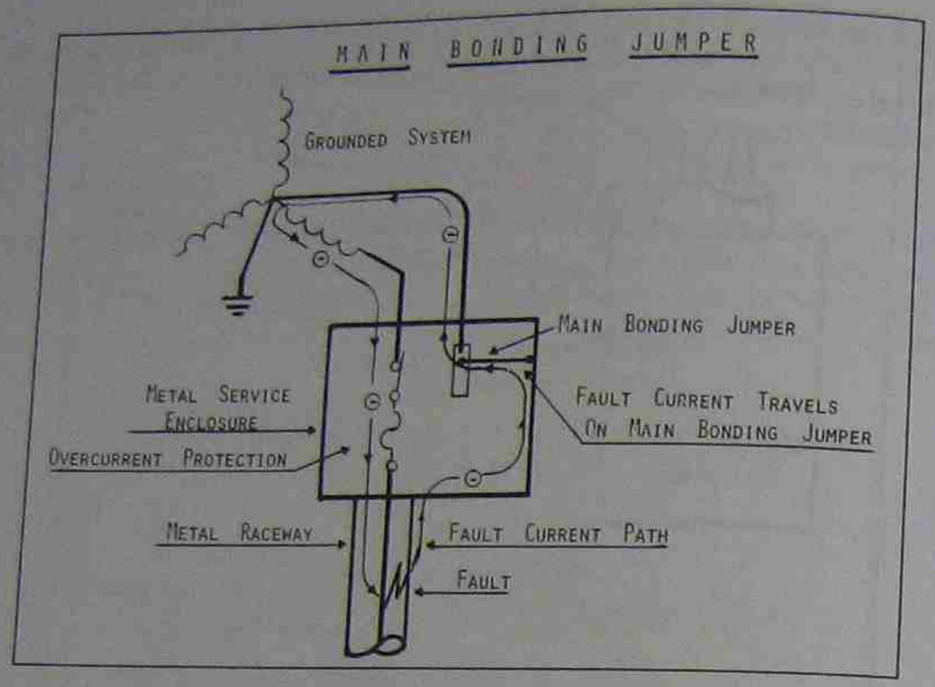

Fig. 9–16 The path of the fault current through the main bonding jumper.

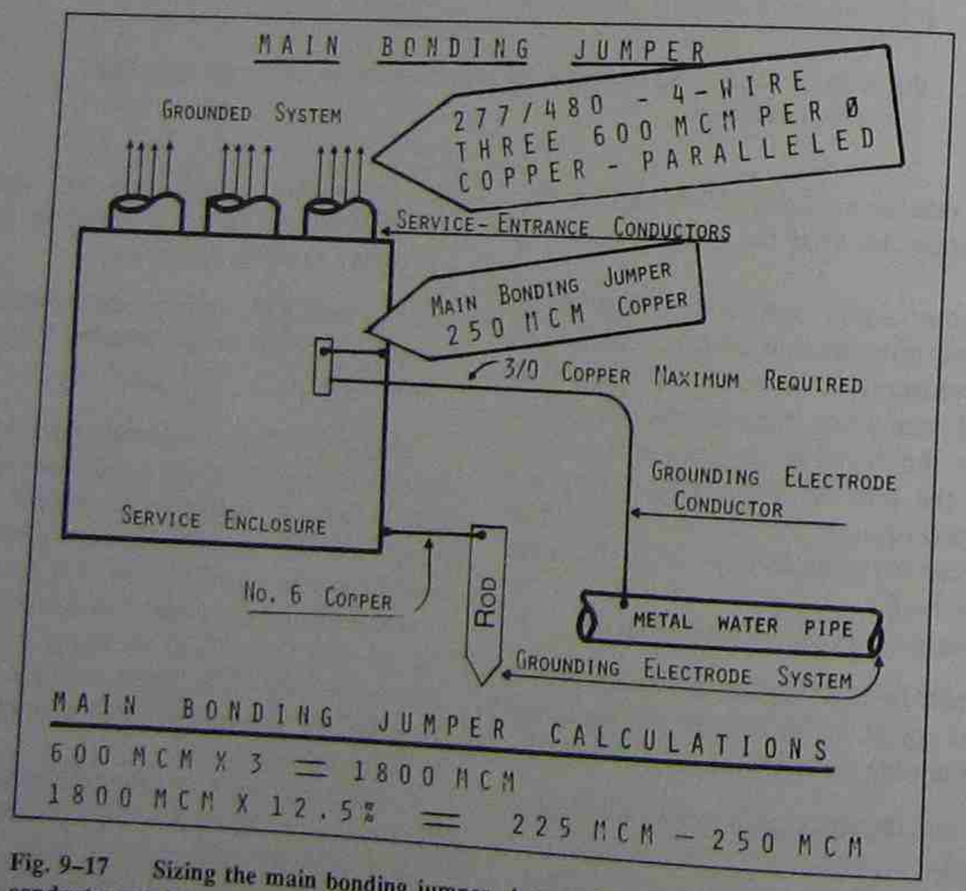

Fig. 9–17 Sizing the main bonding jumper. A case where the grounding electrode conductor can be smaller than the main bonding jumper.

copper and aluminum is different. The third method of calculating the main bonding jumper covers this type of installation.

Figure 9–18 illustrates method 3 for calculating the main bonding jumper size with the use of one 500 MCM, THHN, aluminum conductor per phase for the service-entrance conductors and a copper main bonding jumper. The ampacity of the two different metals is taken into consideration when making this calculation. In this case the service-entrance conductors are assumed, or visualized, to be copper instead of aluminum while making the calculations for the main bonding jumper. *Table 310-16* (figure 9–19) is used for making the transition from aluminum to the equivalent copper conductors. There could be situations where an ampacity table other than *Table 310-16* would be used, but this installation fits into *Table 310-16*.

500 MCM aluminum THHN insulation = 350 amps

Question: What size copper with THHN insulation will be required for 350 amps?

Answer: Table 310-16, for 350 amps with type THHN insulation, requires a 350 MCM copper conductor. Therefore, the service-entrance conductors are assumed to be 350 MCM, THHN copper for calculating the size of the main bonding jumper. Using the 350 MCM read directly from *Table 250-94* (figure 9–20) under copper service-entrance conductors, and read under copper grounding electrode conductor for the size of the main bonding jumper, the

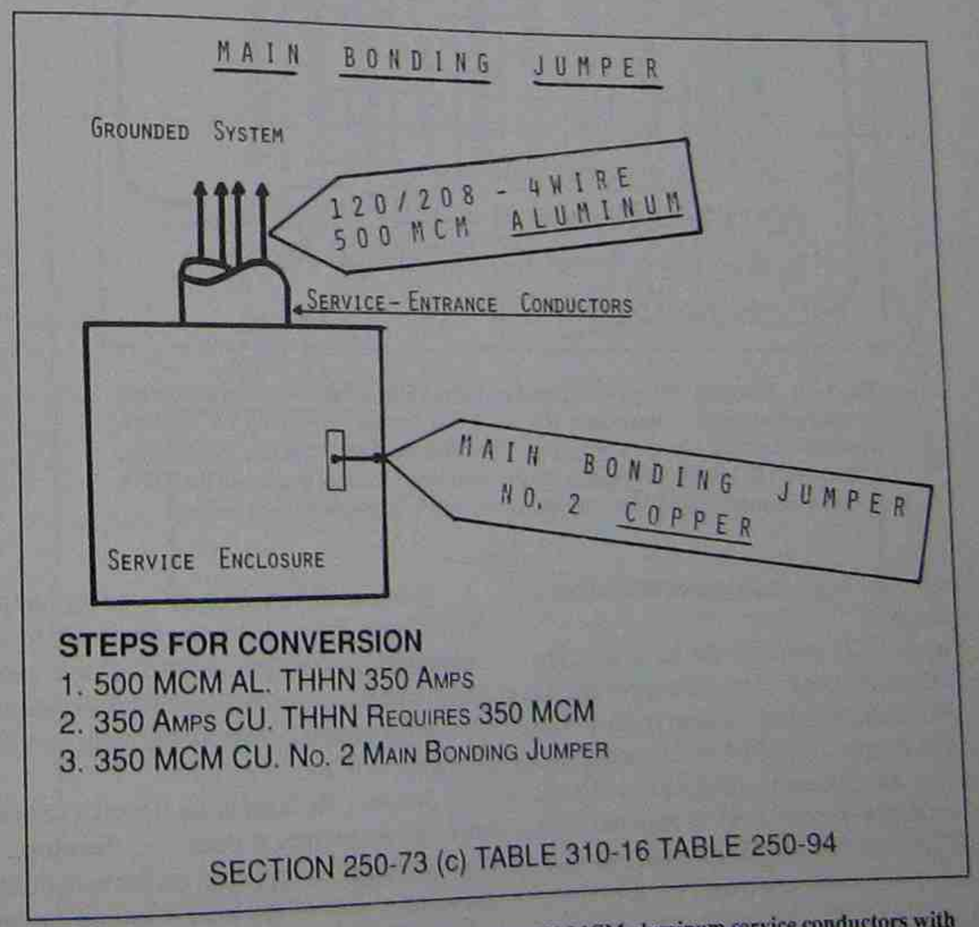

Fig. 9–18 Sizing the main bonding jumper using 500 MCM aluminum service conductors with a copper main bonding jumper.

Table 310-16. Ampacities of Not More than Three Single Insulated Conductors, Rated 0 through 2000 Volts, in Raceway in Free Air and Ampacities of Cable Types AC, NM, NMC and SE

Based on Ambient Air Temperature of 30°C (86°F).

Size	Temperature Rating of Conductor. See Table 310-13								Size
	60°C (140°F)	75°C (167°F)	85°C (185°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	85°C (185°F)	90°C (194°F)	
AWG MCM	TYPES 1TW, 1UF	TYPES 1FFPW, 1RH, 1RHW, 1THW, 1THWN, 1HHW, 1USE, 1XW	TYPE V	TYPES TA, TBS, SA, AVB, SIS, 1FEP, 1FEPB, 1PAH, 1THHN, 1XHHW	TYPES 1TW, 1UF	TYPES 1RH, 1RHW, 1THW, 1THWN, 1XHHW, 1USE	TYPE V	TYPES TA, TBS, SA, AVB, SIS, 1FPAH, 1THHN, 1XHHW	AWG MCM
	COPPER				ALUMINUM OR COPPER-CLAD ALUMINUM				
18				14					
16			18	18					
14	20†	20†	25	25†					
12	25†	25†	30	30†	20†	20†	25	25†	12
10	30	35†	40	40†	25	30†	30	35†	10
8	40	50	55	55	30	40	40	45	8
6	55	65	70	75	40	50	55	60	6
4	70	85	95	95	55	65	75	75	4
3	85	100	110	110	65	75	85	85	3
2	95	115	125	130	75	90	100	100	2
1	110	130	145	150	85	100	110	115	1
1/0	125	150	165	170	100	120	130	135	1/0
2/0	145	175	190	195	115	135	145	150	2/0
3/0	165	200	215	225	130	155	170	175	3/0
4/0	195	230	250	260	150	180	195	205	4/0
250	215	255	275	290	170	205	220	230	250
300	240	285	310	320	190	230	250	255	300
350	260	310	340	350	210	250	270	280	350
400	280	335	365	380	225	270	295	305	400
500	320	380	415	430	260	310	335	350	500
600	355	420	460	475	285	340	370	385	600
700	385	460	500	520	310	375	405	420	700
750	400	475	515	535	320	385	420	435	750
800	410	490	535	555	330	395	430	450	800
900	435	520	565	585	355	425	465	480	900
1000	455	545	590	615	375	445	485	500	1000
1250	495	590	640	665	405	485	525	545	1250
1500	520	625	680	705	435	520	565	585	1500
1750	545	650	705	735	455	545	595	615	1750
2000	560	665	725	750	470	560	610	630	2000

500 MCM ALUMINUM = 350 AMPS AND
IS ASSUMED TO BE EQUAL TO 350 AMPS
COPPER = 350 MCM

Fig. 9–19 Sizing the main bonding jumper. Using *Table 310-16* to convert aluminum to equivalent copper conductors. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright ©, 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

inimum size main bonding jumper required is o. 2 copper.

Figure 9–21 reverses the situation. The rvice-entrance conductors are copper and an uminum main bonding jumper is used. The 0 MCM copper, type THW insulation is rated 0 amps. An aluminum conductor with type IW insulation for 380 amps is required to be 0 MCM. The 750 MCM aluminum service-rance conductors are required to have a imum No. 3/0 aluminum main bonding per.

Question: When the main bonding jumper is a different material than the service-entrance conductors, can you just look in the table under the aluminum conductor size for the service and the copper conductor size for the main bonding jumper?

Answer: No. Sometimes it works out that way and sometimes it does not; therefore, it cannot always be depended on for calculating the correct size of the main bonding jumper when different metals are used.

Table 250-94
Grounding Electrode Conductor for AC Systems

Size of Largest Service-Entrance Conductor or Equivalent Area for Parallel Conductors		Size of Grounding Electrode Conductor	
Copper	Aluminum or Copper-Clad Aluminum	Copper	*Aluminum or Copper-Clad Aluminum
2 or smaller	0 or smaller	8	6
1 or 0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250 MCM	4	2
Over 3/0 thru 350 MCM	Over 250 MCM thru 500 MCM	2	0
Over 350 MCM thru 600 MCM	Over 500 MCM thru 900 MCM	0	3/0
Over 600 MCM thru 1100 MCM	Over 900 MCM thru 1750 MCM	2/0	4/0
Over 1100 MCM	Over 1750 MCM	3/0	250 MCM

Fig. 9–20 Reading *Table 250-94* for sizing the main bonding jumper for the service illustrated in figure 9–18. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright ©, 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

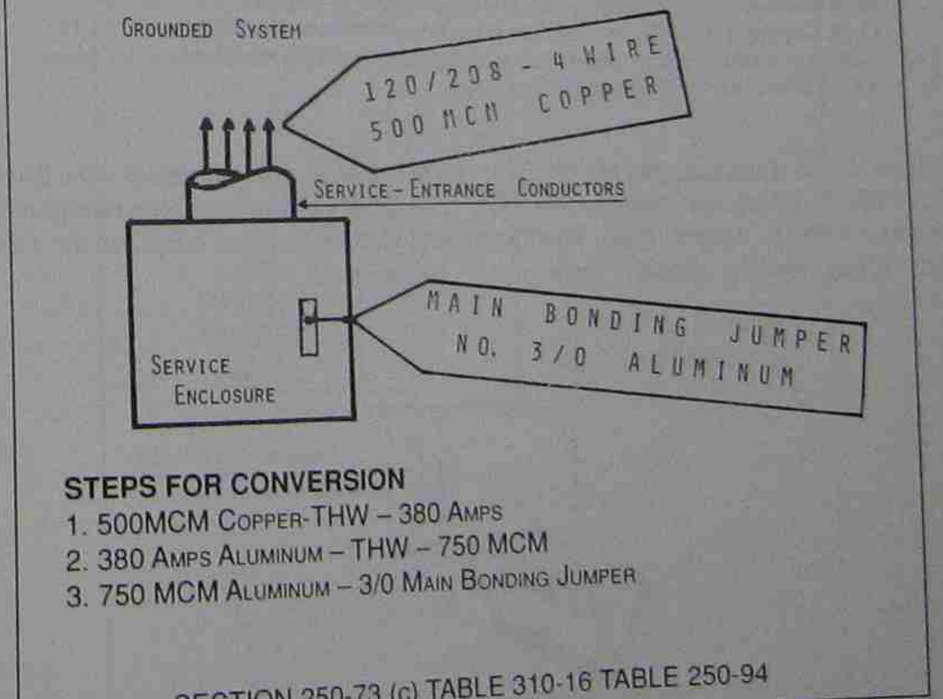

Fig. 9–21 Sizing the main bonding jumper using 500 MCM copper service conductors with an aluminum main bonding jumper.

SERVICE 250 MCM ALUMINUM THHN
MAIN BONDING JUMPER COPPER

STEPS FOR CONVERSION
250 MCM AL. THHN 230 AMPS
230 AMPS CU. THHN 4/0
4/0 COPPER REQUIRES No. 2

Table 250-94
Grounding Electrode Conductor for AC Systems

Size of Largest Service-Entrance Conductor or Equivalent Area for Parallel Conductors		Size of Grounding Electrode Conductor	
Copper	Aluminum or Copper-Clad Aluminum	Copper	*Aluminum or Copper-Clad Aluminum
2 or smaller	0 or smaller	8	6
1 or 0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250 MCM	4	2
Over 3/0 thru 350 MCM	Over 250 MCM thru 500 MCM	2	0
Over 350 MCM thru 600 MCM	Over 500 MCM thru 900 MCM	0	3/0
Over 600 MCM thru 1100 MCM	Over 900 MCM thru 1750 MCM	2/0	4/0
Over 1100 MCM	Over 1750 MCM	3/0	250 MCM

Fig. 9–22 Comparing the use of calculations to the direct use of *Table 250-94* to size the main bonding jumper. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright ©, 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

Figure 9–22 illustrates the use of 250 MCM, THHN, aluminum service-entrance conductors, with a copper main bonding jumper. When reading directly from the *Table 250-94*, No. 4 copper is indicated. When calculated using the ampacity ratings of copper and aluminum, No. 2 copper is the minimum size required.

CHAPTER 10

Equipment Grounding Conductor

This chapter focuses on the equipment grounding conductor (figure 10–1). Discussed are its purpose, use, types, identification, installation, connection, and sizing.

The equipment grounding conductor is one of the conductors that ties into the bull's eye of the overall grounding system at the service equipment. It is used for grounding metal enclosures containing current-carrying conductors and metal enclosures of electrical equipment.

DEFINITION OF *EQUIPMENT GROUNDING CONDUCTOR*

The equipment grounding conductor plays no part in the electrical lighting or power circuit. But it plays a very important part in ensuring safety in the grounding system. "Equipment Grounding Conductor" is defined in *Article 100* (figure 10–2).

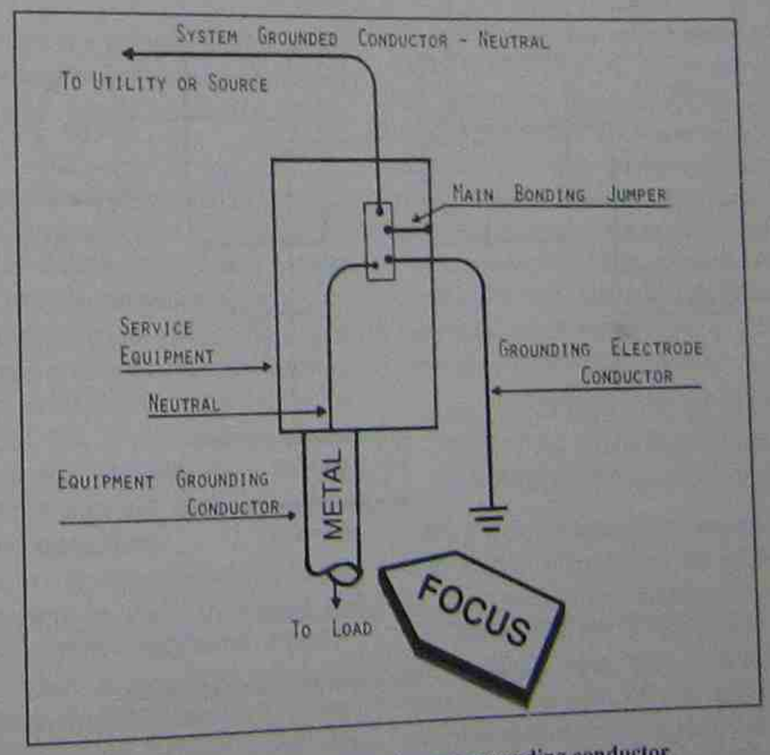

Fig. 10–1 Focus on the equipment grounding conductor.

Quote – "The conductor used to connect the noncurrent-carrying metal parts of equipment, raceways, and other enclosures to the system grounded conductor and/or the grounding electrode conductor at the service equipment or at the source of a separately derived system."*

Comment: The term *and/or* indicates that when there is a grounded system, the equipment grounding conductor is connected to the grounded conductor and the grounding electrode conductor. When there is an ungrounded system and no grounded conductor, the equipment grounding conductor is connected to the grounding electrode conductor.

DEFINITION OF *SYSTEM*

Figure 10–3 is a very basic illustration of a *system*. The definition given is not taken from the Code.

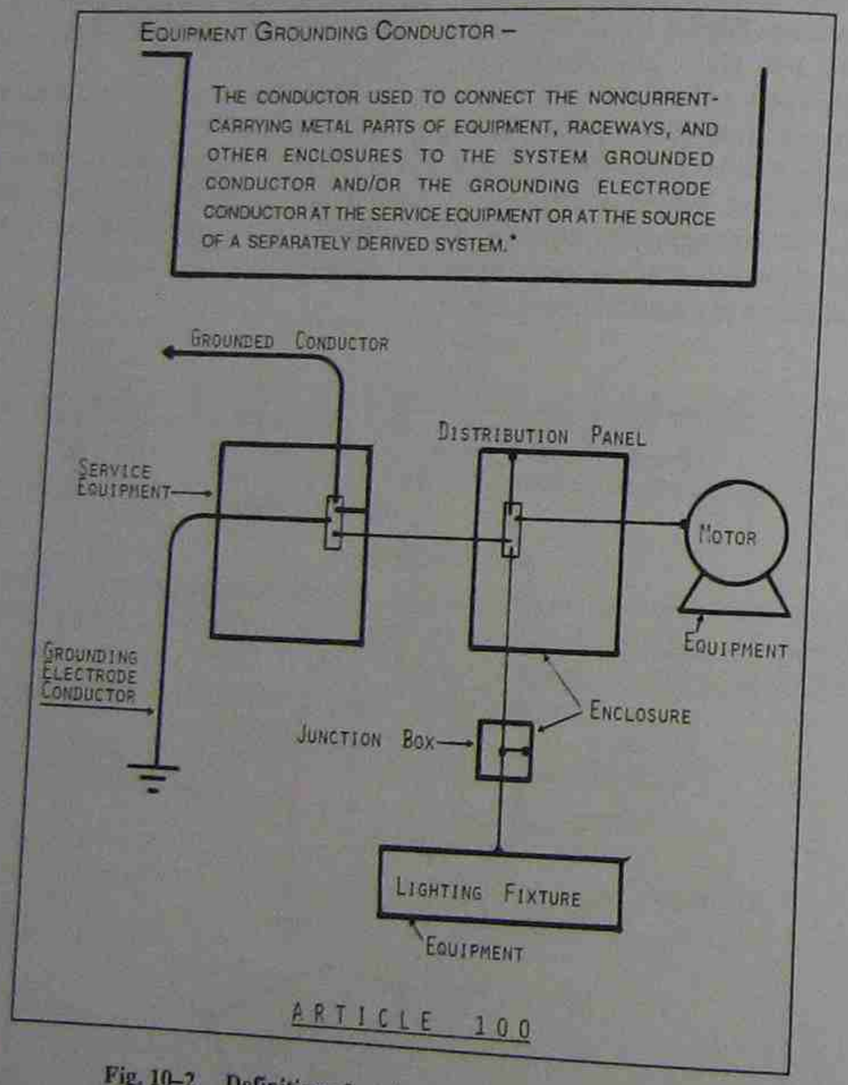

Fig. 10–2 Definition of *equipment grounding conductor.*

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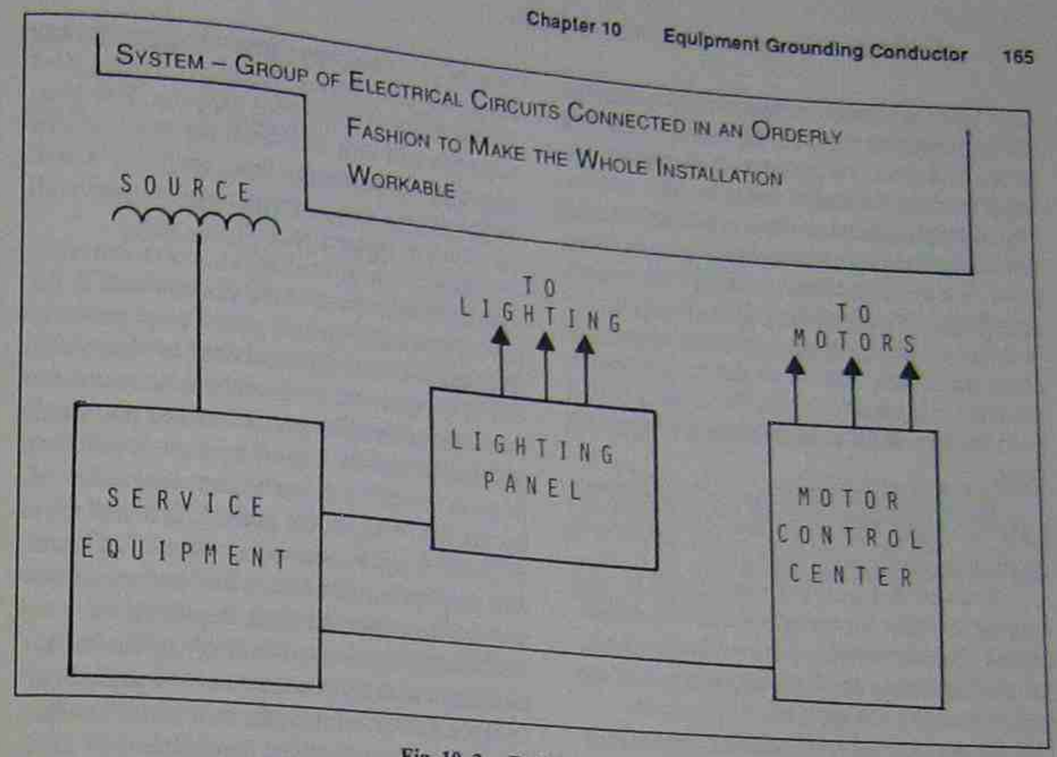


Fig. 10–3 Definition of *system.*

> "A system is a group of electrical circuits connected in an orderly fashion to make the whole installation workable."

The term *system* is often used in the field just to indicate the connection at the source of supply—such as a three-wire system, a delta system, a wye system, or another type of connection—and not the entire system the supply feeds. One should not be misled into believing that the system is only the connection at the source of supply. The system includes all the distribution feeders, the branch circuit, all electrically operated equipment, and all electrical and mechanical connections.

Question: In a system as simple as the one illustrated, at how many points throughout the system would electrical connections be made?

Answer: When counting the electrical connections for the service-entrance conductor, the feeder, going to the lighting panel, the branch circuits going to the individual lights, the connections at the lighting fixture, feeder connections for the motor control center, the motor branch circuits, the motor connections, and control connections, the result would be a very large number. These electrical connections must be made with care to maintain continuity of the electrical circuit and make sure all the electrical equipment operates satisfactorily.

Section 300-13 requires the continuity of conductors to be maintained. There is another very good reason that every one of these connections should be made properly:

THE POINT OF CONNECTION IS THE POINT AT WHICH THE HIGHEST NUMBER OF FAULTS TAKE PLACE.

Very few faults take place between conductors in the middle of a conduit run. Most faults occur at or near the point of connection or termination.

Look once again at the same system (figure 10–3). Only this time, look at it from a mechanical viewpoint of the installation of the raceways and enclosures. How many "mechanical" connections will be made to complete the installation properly?

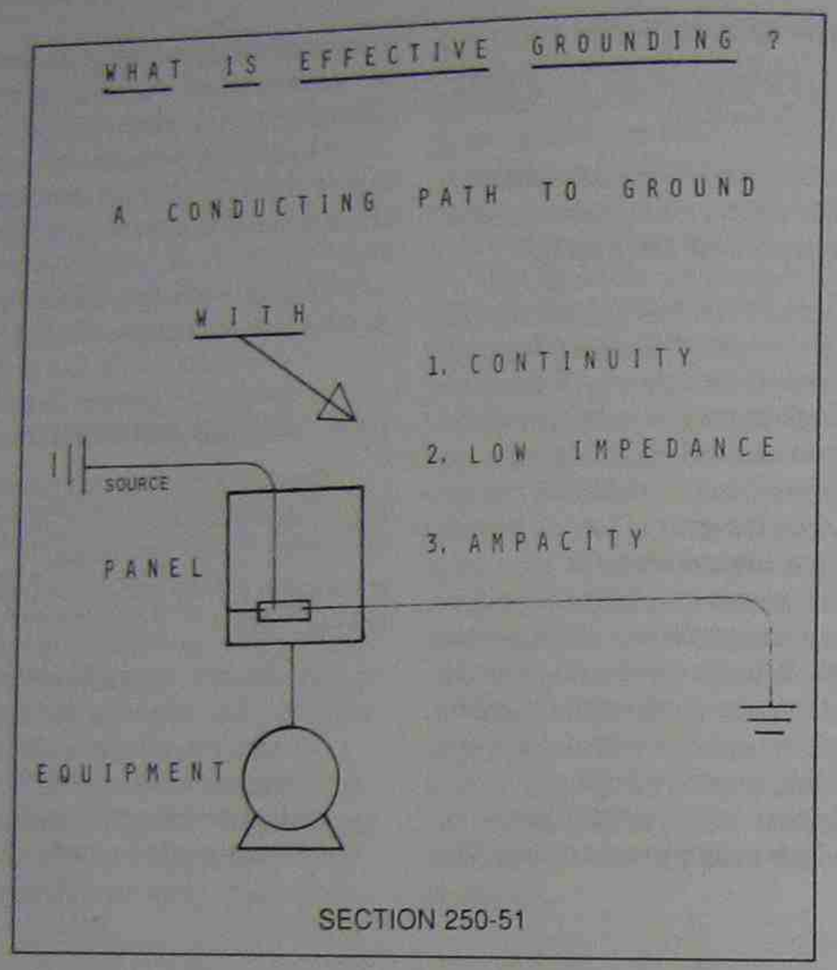


Fig. 10–6 Establishing an effective grounding path.

2. Low impedance—Keep the opposition to the flow of current as low as possible.
3. Ampacity—It must be of sufficient size to be able to carry the current the equipment may be required to carry under fault conditions.
4. The earth shall not be used as the sole equipment grounding conductor.

UNDER *FAULT* CONDITIONS, *GROUNDING* IS THE *ELECTRICAL CIRCUIT*. THE *GROUNDING CIRCUIT* IS *PLANNED* AND *PREPARED* FOR, JUST AS IF THE *FAULT* WERE REALLY GOING TO *HAPPEN*.

Engineers work at designing electrical installations with no faults. The electrician works at installing electrical circuits with no faults. But work at it as they may, no one has yet built the perfect electrical circuit, one without a possible fault. Electrical faults are like other accidents—it is not known when or where the accident is going to take place. We learn from past experiences and do the best we can to protect against electrical accidents in the future.

When there is a splice to be made in an electrical installation, as shown in figure 10–7, it must be made with care to ensure proper electrical continuity for the electrical circuit. When a splice is made in a run of metal conduit, it must be made with the same care. The fitting in the metal conduit becomes an electrical splice in an electrical circuit when electrons travel on the equipment grounding conductor under fault conditions or to drain static electricity.

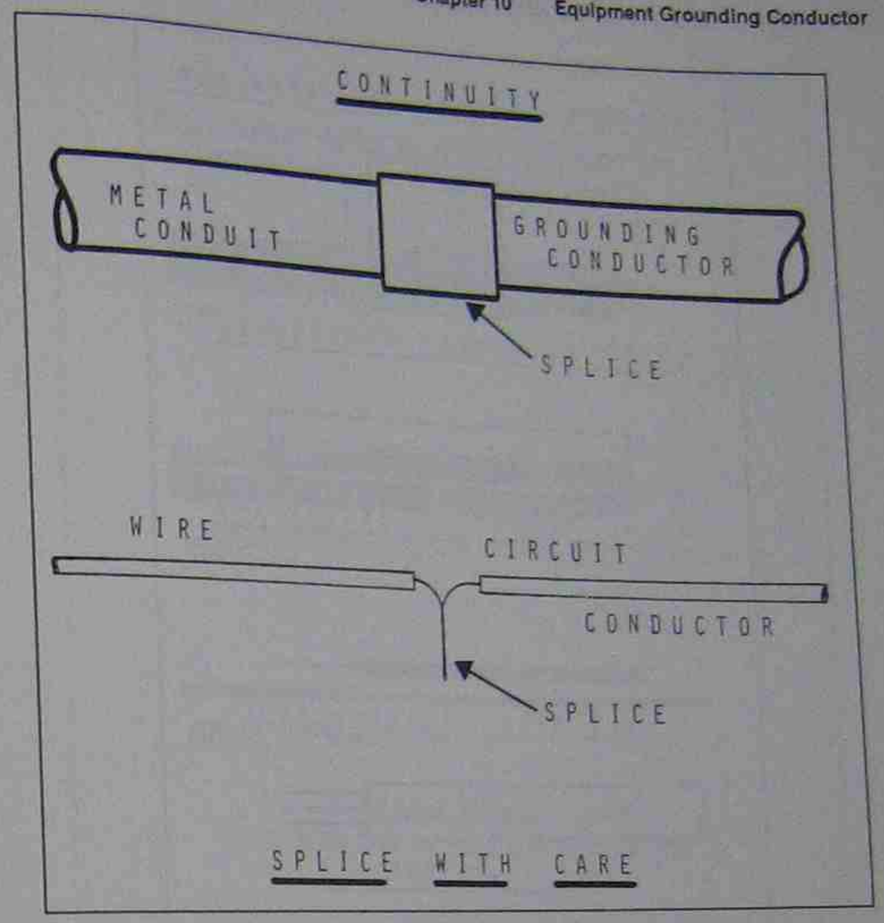


Fig. 10–7 Splicing with care to ensure continuity.

TYPES OF EQUIPMENT GROUNDING CONDUCTORS

The equipment grounding conductor may be a metal raceway, a metal enclosure, or an electrical conductor (as illustrated in figure 10–8) or a combination of metal raceway, enclosures, and conductors. More often than not, it is a combination of all of these.

WIRED USED FOR EQUIPMENT GROUNDING CONDUCTOR

When an electrical conductor is used, it can be either solid or stranded, insulated or bare. However, there are situations where the Code requires an insulated equipment grounding conductor, such as *Section 680-20(b)(1* requires for swimming pools, illustrated i figure 10–9.

IDENTIFICATION OF EQUIPMENT GROUNDING CONDUCTOR

Sections 250-57(b) and *310-12(b)*, lustrated in figure 10–10, set down the basic r for the color of the outer finish of the equipm grounding conductor when it is installed i raceway, cable, or cord. The color green reserved for the equipment grounding cond tor. Green identifies the equipment ground conductor. Green with one or more yell stripes is also permitted to be used for an eq ment grounding conductor. *Section 200-1*

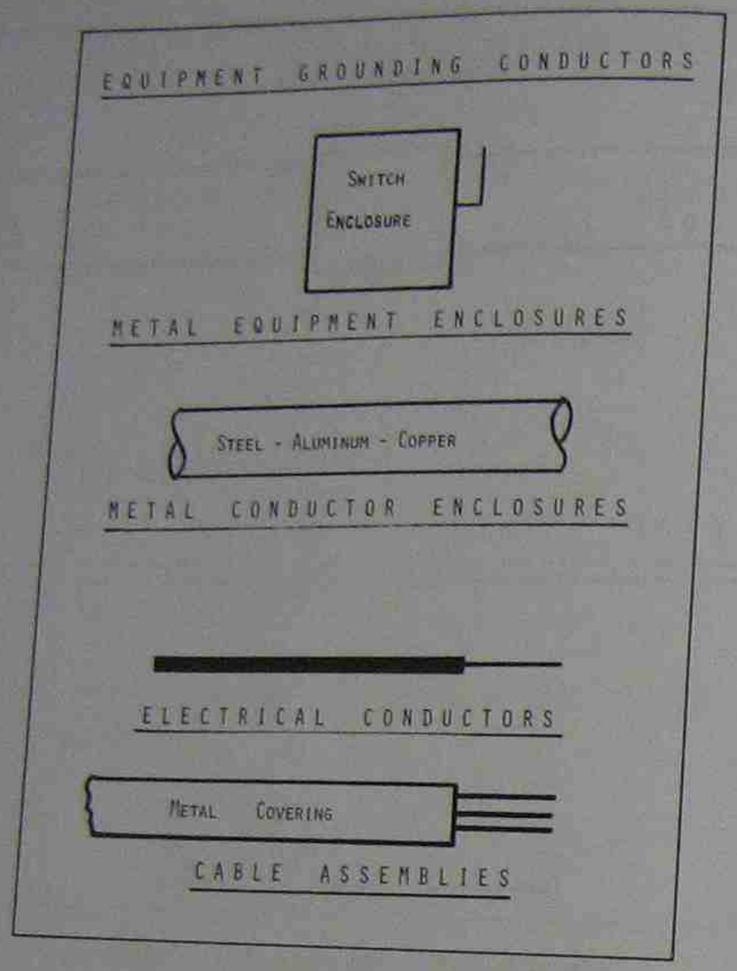


Fig. 10–8 Types of equipment grounding conductors.

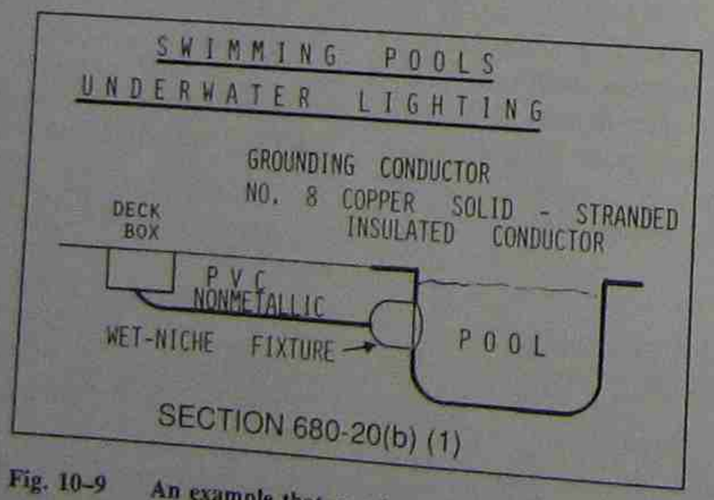


Fig. 10–9 An example that requires an insulated equipment grounding conductor.

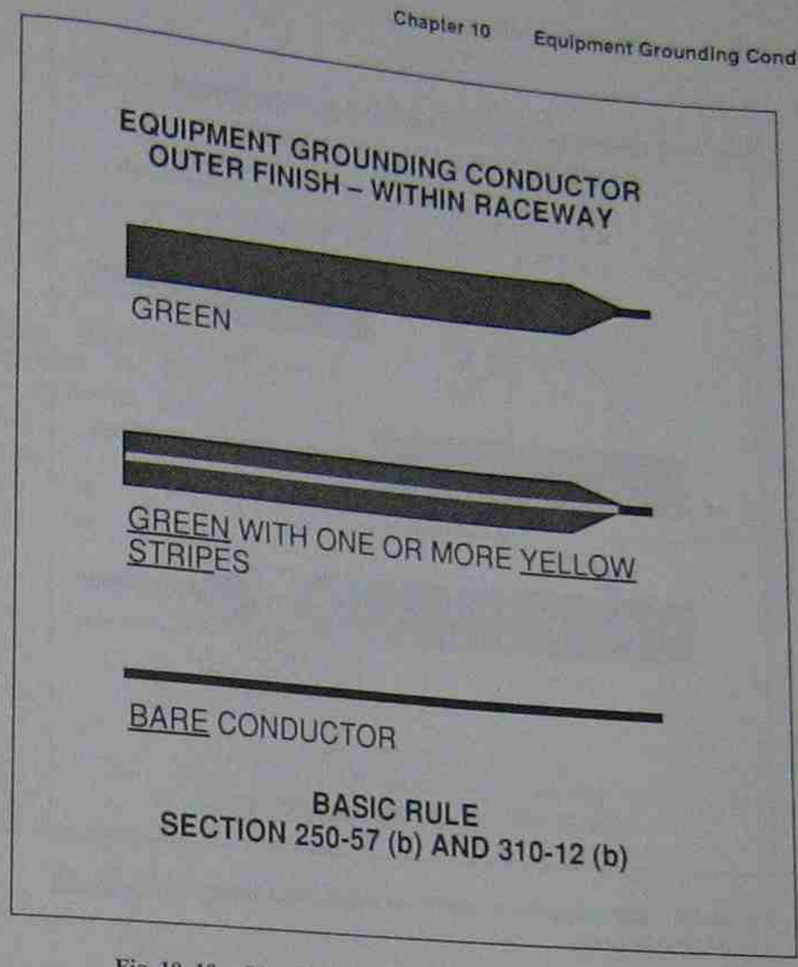


Fig. 10–10 Identifying the equipment grounding conductor.

specifies that the green color scheme also be used for the terminals of receptacles of the equipment grounding conductor.

Section 250-57(b), Exception No. 1 permits the use of an insulated conductor for the equipment grounding conductor installed in raceways to have an outer covering other than green (figure 10–11). The following is a breakdown of Exception No. 1 as it applies to a *single electrical conductor*, other than a green one, being installed for the equipment grounding conductor.

1. The conductor is larger than No. 6.
2. The conductor can be copper or aluminum.
3. The conductor must be permanently identified as the equipment grounding conductor.
4. The identification must be made at each termination and at every point the conductor is accessible. This includes pull and junction boxes.

Comment: This exception does not apply to a No. 6 conductor. Note the "larger than." The smallest conductor that could be used would be a No. 4 copper or No. 4 aluminum. It is unusual that the Code recognizes the same size copper or aluminum conductor for a particular installation. The identification must be made at all terminations and at all pull or junction boxes that the equipment grounding conductor passes through and where the conductor is accessible.

5. The various ways to identify the conductor are as follows:

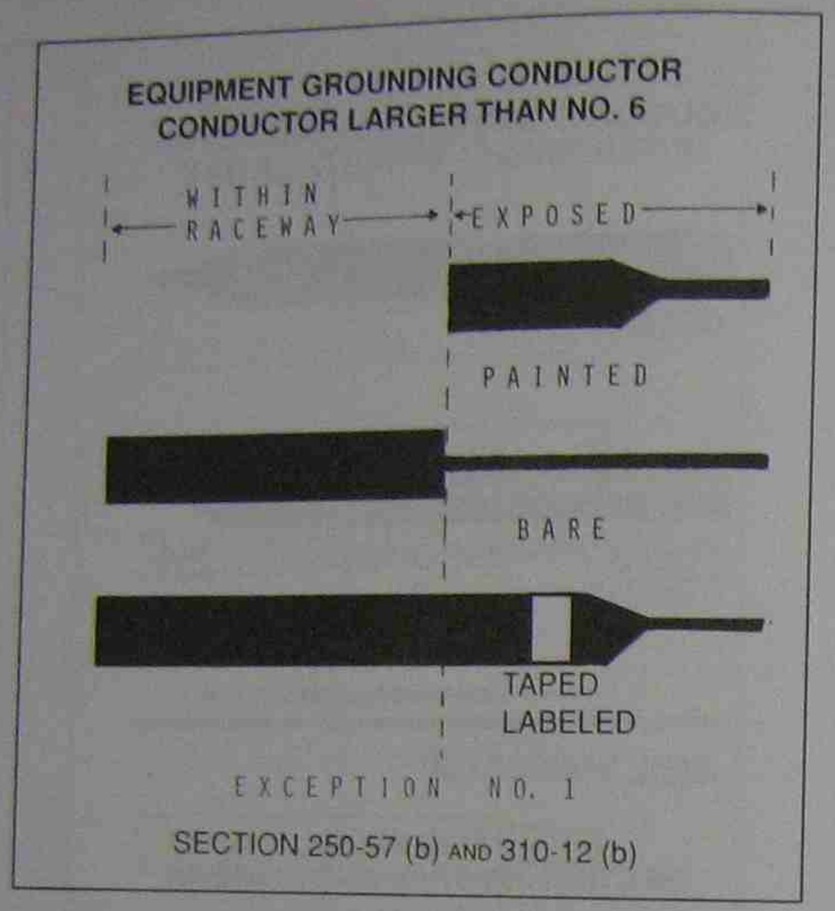


Fig. 10–11 Exception No. 1 to the basic rule for identifying the equipment grounding conductor.

a. Strip the insulation off the entire length of the exposed conductor at the termination or where it is accessible to make it look like a bare conductor.
b. Color the insulation green by using green paint or green sleeving.
c. Mark exposed insulation with green tape, labels, or some durable means of identification.

The following is a breakdown of Exception No. 3 as it applies to *multiconductor cable* using other than a green-colored conductor within the cable for the equipment grounding conductor.

Comment: The phrase "at the time of installation" puts the responsibility of marking the cable on the electrician who installs the cable. If the cable should be opened in a junction box or terminal box, the equipment grounding conductor will have to be identified.

1. The installation is restricted to areas where only qualified persons will service the installation.
2. The conductor shall be marked at each termination and at every point where the conductor is accessible.
3. The marking shall be permanent.
4. The marking and identification shall take place at the time of installation.
5. Methods permitted for identification include the following:
   a. Strip the insulation from the entire exposed length of the conductor.
   b. Color or paint the exposed insulation green.
   c. Mark the insulation with green tape.
   d. Use green-colored adhesive labels.

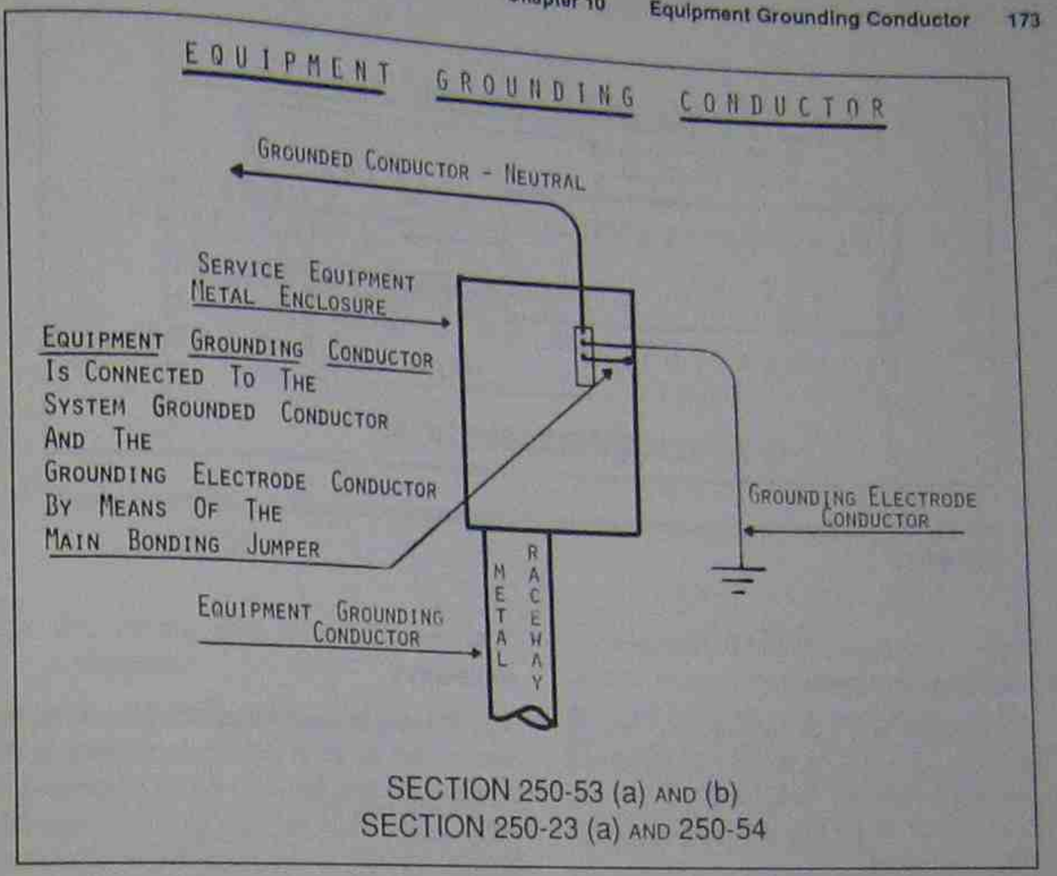


Fig. 10–12 Required connection of the equipment grounding conductor.

INSTALLATION OF EQUIPMENT GROUNDING CONDUCTOR

The equipment grounding conductor furnishes a low-impedance path to the service equipment. At the service equipment, it is connected to the grounding electrode conductor, which furnishes the path to the grounding electrode.

At Service Equipment

Sections 250-23(a) and *250-53(a)* require the equipment grounding conductor to be connected to the system grounded conductor, the main bonding jumper, and the grounding electrode conductor at the service equipment, as illustrated in figure 10–12. *Section 250-54* requires the equipment grounding conductor to be connected to the common grounding electrode.

Using the Circuit Conductor Raceway

Section 250-57(b) requires the equipment grounding conductor to be installed in the same raceway or cable as the circuit conductors, as illustrated in figure 10–13.

Reason: Under normal conditions there is no current flow in the equipment grounding conductor. When there is a fault, there is a current flow in the equipment grounding conductor. The current flow in the equipment grounding conductor is being fed to the fault by one of the circuit conductors and the equipment grounding conductor is acting as the return path. If the feed and return conductor are as close together as possible, the impedance caused by induction due to the alternating current will be held as low as possible.

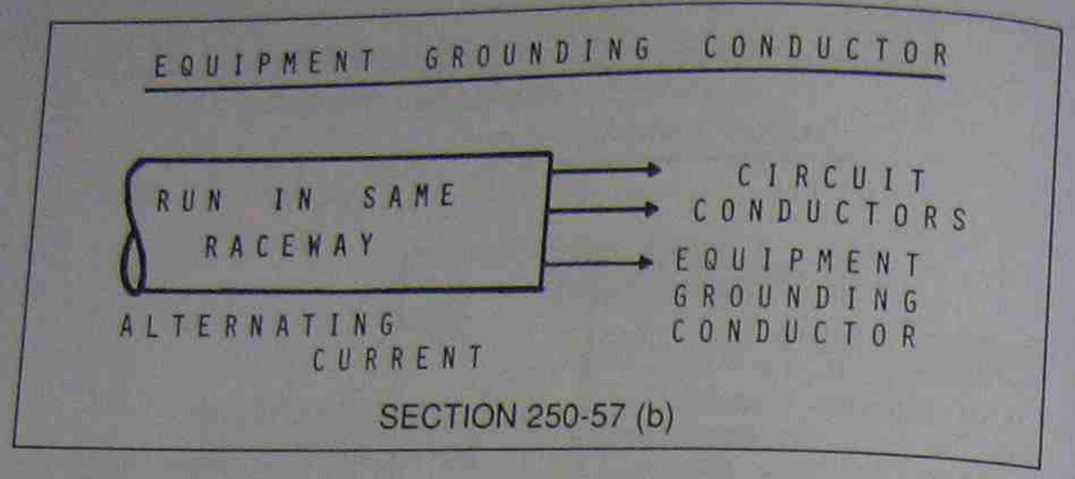


Fig. 10–13 The equipment grounding conductor installed in the same raceway as the AC circuit conductors.

Direct-Current System

Exception No. 2 of *Section 250-57(b)*, illustrated in figure 10–14, permits the equipment grounding conductor installed with a direct-current circuit to be run separately from the circuit conductors.

Reason: There is no impedance due to inductance in a direct-current circuit, because there is no alternating magnetic field.

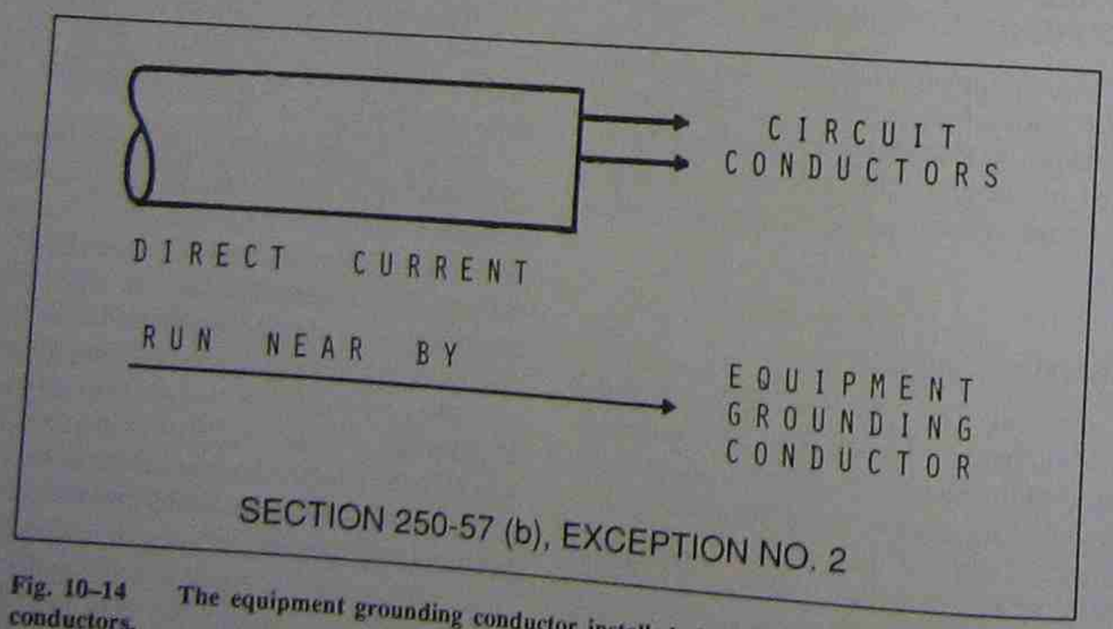


Fig. 10–14 The equipment grounding conductor installed close to the raceway with the DC conductors.

Raceways

The requirement for all conductors of the same circuit to be in the same raceway is repeated in *Section 300-3(b)* and is illustrated in figure 10–15. Note the various conductors this section requires to be installed in the same raceway when a raceway is used. These are:

1. All phase conductors.

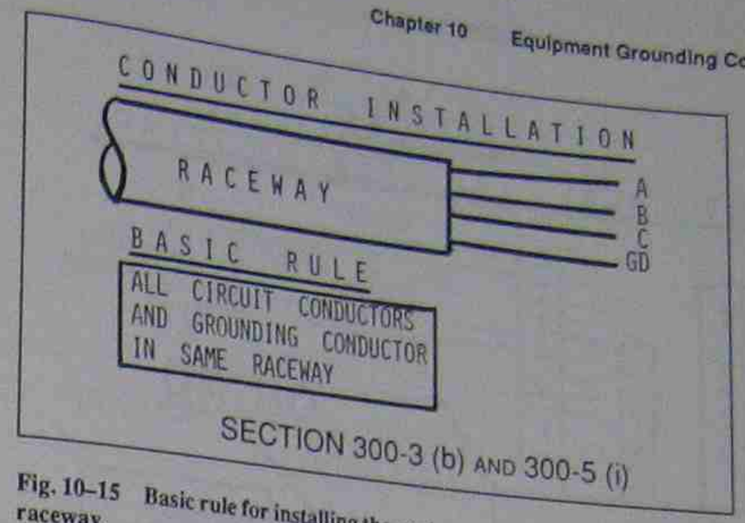


Fig. 10–15 Basic rule for installing the equipment grounding conductor in a raceway.

2. The neutral (the grounded) conductor, when used.
3. The equipment grounding conductor, when required.
4. When the circuit conductors are not installed in a raceway but in a trench as direct burial, the equipment grounding conductor is required to be in the same trench or close by.

Comment: When the installation is made with a metal raceway and the raceway has continuity, the metal raceway is permitted to be the equipment grounding conductor and there would be no equipment grounding conductor installed in the conduit. However, if the raceway is nonmetallic, such as PVC, then an equipment grounding conductor is required and must be installed in the same raceway as the circuit conductors.

Figure 10–16 illustrates a violation of *Section 250-57(b)*. The equipment grounding conductor is not installed with the circuit conductors. This connection can be found on electrical installations. It will accomplish one thing: it will maintain the two pieces of equipment at the same potential. Its disadvantage is that it will provide a potential path for circulating ground currents and will contribute to creating "dirty electricity" for microelectronic or high-tech equipment.

Figure 10–17 illustrates the use of parallel conductors installed in two nonmetallic raceways, with one set of phase conductors (A, B, and C) in each raceway, as permitted by *Section 310-4*. The requirements of *Section 250-95* and Exception No. 1 of *Section 300-5(i)* are also included. When the raceway is not metal, for example if it is PVC, an equipment grounding conductor is required in each raceway.

Figure 10–18 illustrates the use of parallel conductors installed in nonmetallic raceways with all phase A conductors in one raceway, all phase B conductors in one raceway, and all phase C conductors in one raceway, as permitted by *Section 310-4*. The requirement of *Section 250-95* and Exception No. 2 of *Section 300-5(i)* are also included. This type of installation can only be made using a nonmetallic raceway. Therefore, an equipment grounding conductor is required to be installed in each raceway. When equipment grounding conductors are used with conductors in parallel, they shall comply with the requirements for conductors in parallel (*Section 310-4*), except that the equipment grounding conductor shall be sized in accordance with *Table 250-95*. This is a very important exception. It is one of the few places in the Code where an exception is still part of the section.

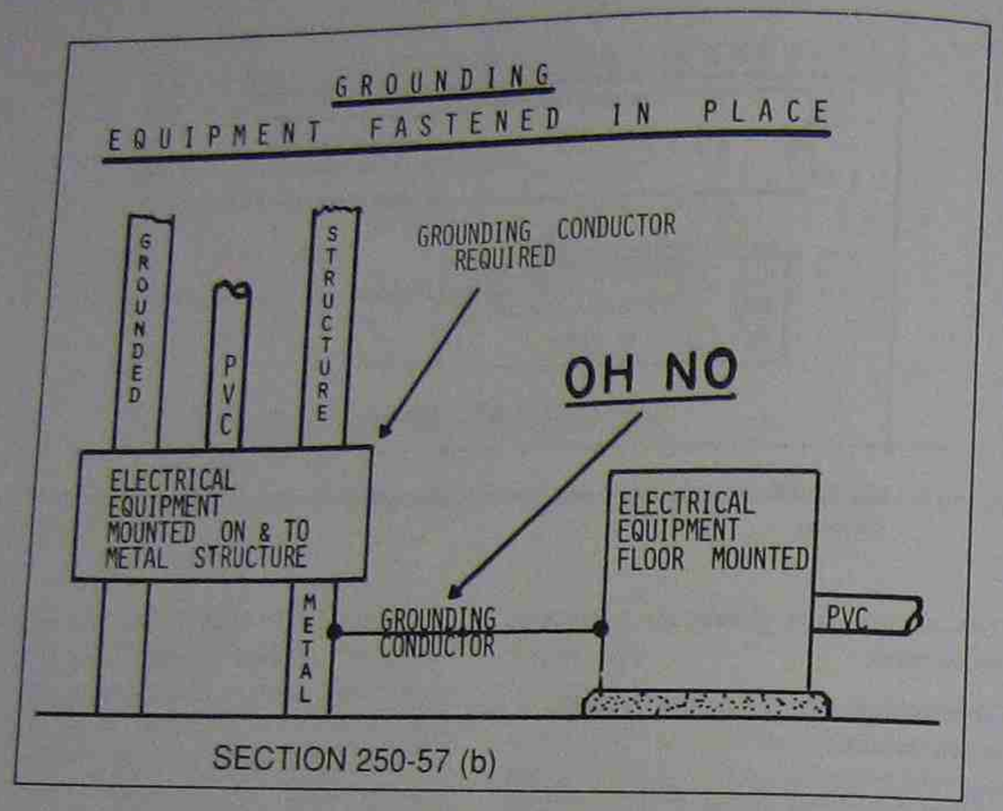


Fig. 10–16 Violation of the requirement for installing the equipment grounding conductor.

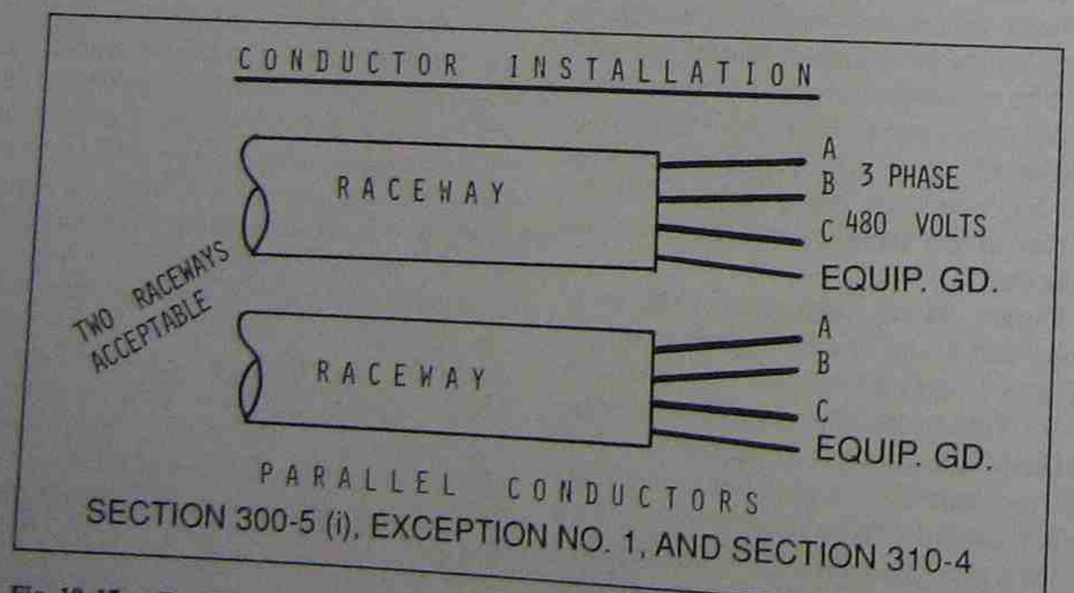


Fig. 10–17 Parallel feeder conductors installed in two raceways with an equipment grounding conductor in each raceway.

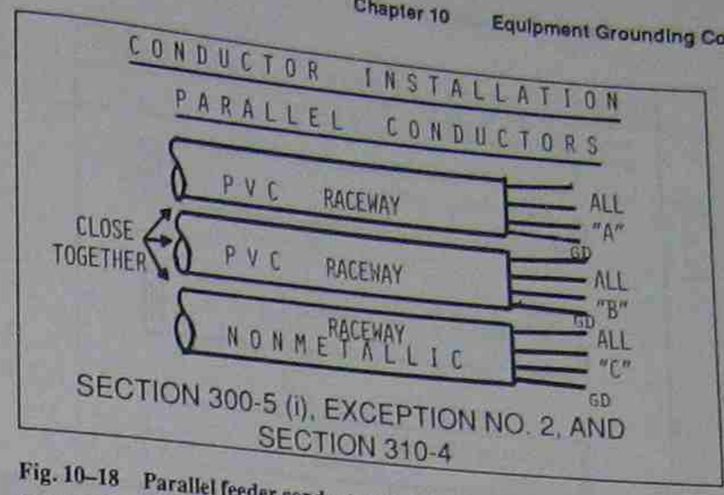


Fig. 10–18 Parallel feeder conductors installed in nonmetallic raceway with an equipment grounding conductor in each raceway.

RACEWAYS AS EQUIPMENT GROUNDING CONDUCTORS

Section 250-91(b) contains a list of various types of equipment grounding conductors. The section also permits the equipment grounding conductor to be a metal raceway, a conductor, or a combination of any of the recognized types of equipment grounding conductors. The list in this section is rather long. It should also be noted that some of the recognized types of equipment grounding conductors listed have limitations placed on them, especially where flexible metal conduits are used. The following is a list of materials permitted to be used for equipment grounding conductors.

1. Copper or other corrosion-resistant conductor
   a. Aluminum or copper-clad aluminum
   b. Solid or stranded
   c. Insulated, covered, or bare
   d. A wire or bus bar of any shape
2. Rigid metal conduit (RMC)
3. Intermediate metal conduit (IMC)
4. Electrical metallic tubing (EMT)
5. Flexible metal conduit, to be used only when both the flex and the fittings are listed for grounding; commonly known as "greenfield"
6. Armor of Type AC cable (BX)
7. The sheath of mineral-insulated, metal-sheathed cable (MI cable)
8. The metal sheath of Type MC cable (armored cable)
9. A combination of the metal sheath and grounding conductors of Type MC cable
10. Cable tray; *Sections 318-2(c)* and *318-6* requirements for the use of cable tray as the equipment grounding conductor
11. The grandfather clause—other electrically continuous metal raceways listed for grounding

Metal Raceways

Figure 10–19 illustrates some of the metal raceways listed in *Section 250-91(b)* for use as the equipment grounding conductor. These steel raceways take the place of the conductor discussed previously. In order for this to be successful, all joints and connections of the metal raceway system must be mechanically secure to ensure a path for the current to flow that will have continuity and a low impedance.

Figure 10–20 illustrates the definition of a *raceway*. Note the one phrase, "with additional functions as permitted by this Code," in the definition of *raceway*. This phrase was inserted

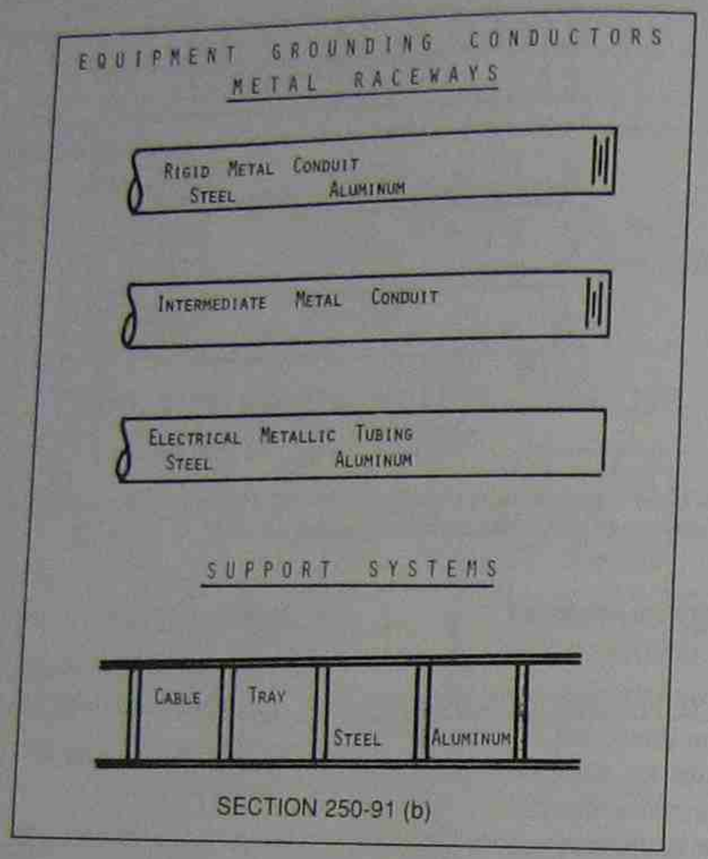


Fig. 10–19 Metal raceways that can be used as equipment grounding conductors.

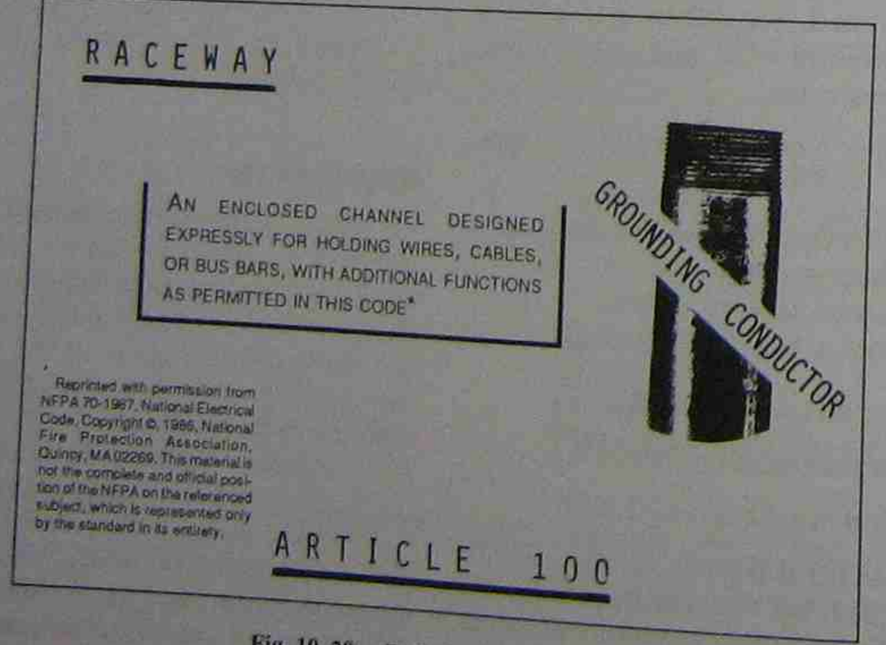


Fig. 10–20 Definition of *raceway*.

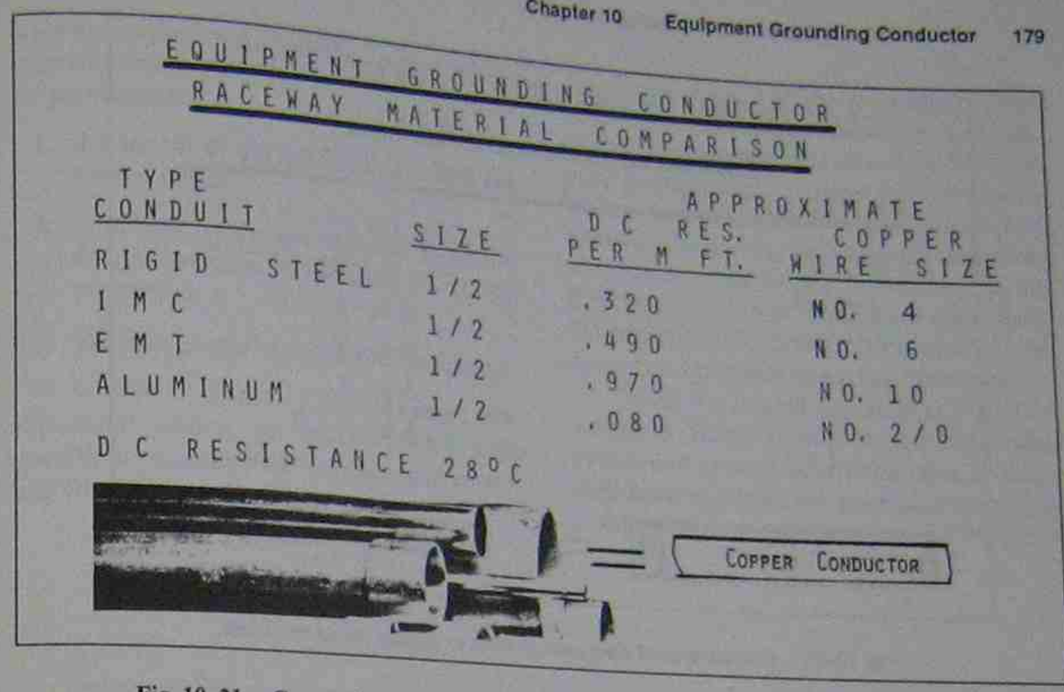


Fig. 10–21 Comparison of metal raceway's resistance to copper conductor resistance.

in the definition so that the metal raceways could be used as equipment grounding conductors.

Question: How do the various metal raceways used for equipment grounding conductors compare with a copper conductor in their ability to conduct the electron flow?

Answer: An accurate comparison cannot be made because of the unknown ambient temperatures in which the raceways might be installed. Figure 10–21 uses approximate values for the illustration. It shows the resistance per 1000 feet of various metal conduit-type raceways and the copper wire size with a comparable resistance per 1000 feet. Aluminum is often used for an electrical circuit conductor. Note how the resistance of 1/2-inch aluminum conduit is approximately as low as the resistance of a No. 2 copper conductor.

The IMC has approximately 62 percent as much cross-sectional area as rigid steel conduit. EMT has approximately 22 percent of the cross-sectional area of rigid steel conduit. As the size of the conduit increases, the cross-sectional area of the metal in the conduit increases.

Reason: The resistance of a conductor is inversely proportional to its cross-sectional area. This means the resistance of the conductor will decrease as the cross-sectional area of the conductor increases.

Figure 10–22 illustrates some wire size comparisons for rigid steel conduit. IMC and EMT would be proportional in cross-sectional area, as they were in figure 10–21.

Metal-Covered Cable Assemblies

Figure 10–23 illustrates two types of cable assemblies with a metal outer sheath that are permitted to be used as the equipment grounding conductor.

Flexible Metal Conduit

Section 250-91(b) permits the use of flexible metal conduit (greenfield) as an equipment grounding conductor. However, there are limitations placed on its use by Exception No. 1, and all the conditions must be met before it can be used as an equipment grounding conductor

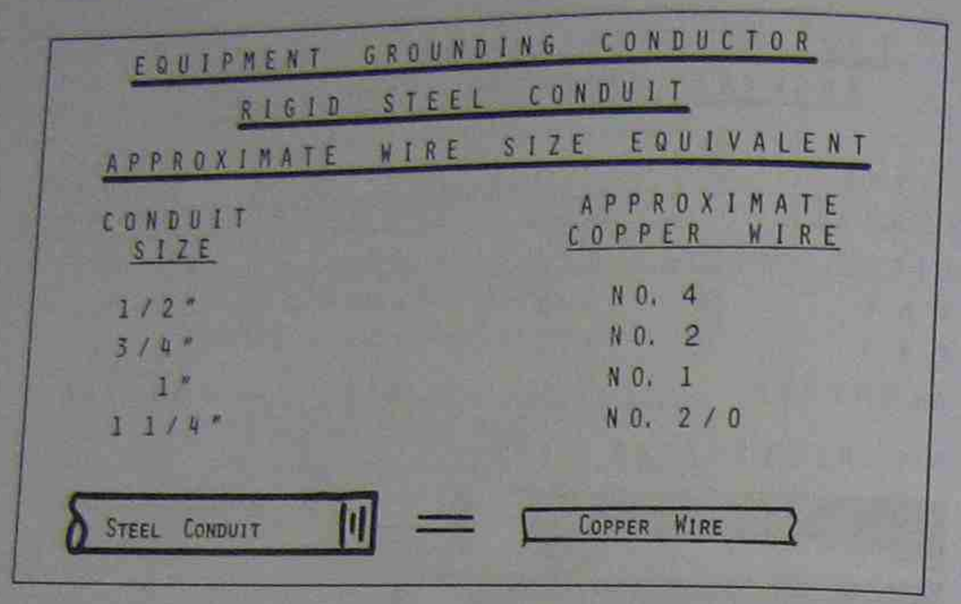


Fig. 10–22 Comparison of steel conduit sizes to copper conductor sizes.

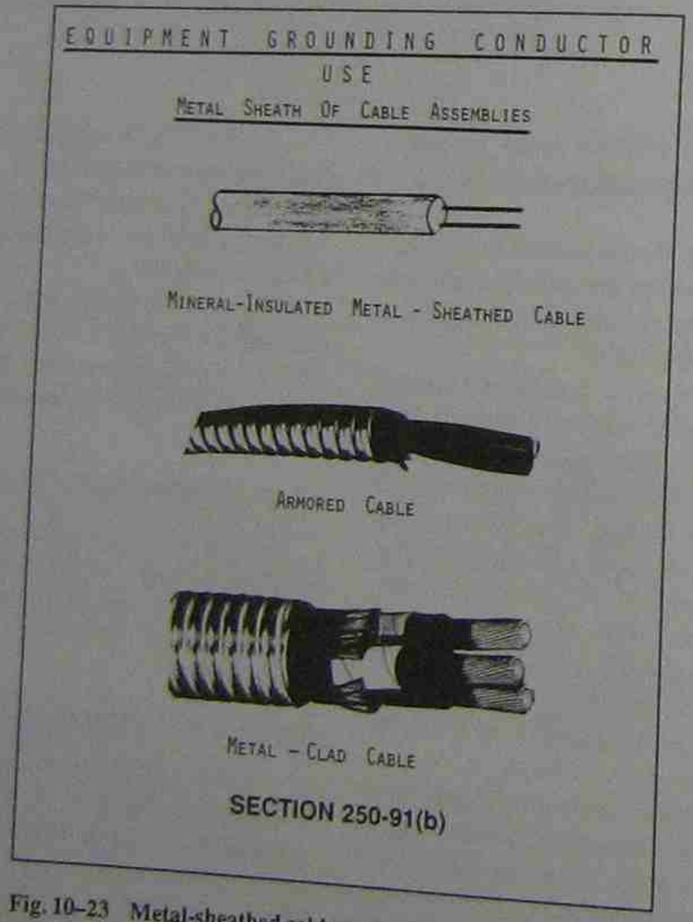


Fig. 10–23 Metal-sheathed cable assemblies permitted to be used as equipment grounding conductors.

This exception covers both the metal conduit-type flex and metal tubing-type flex. Both shall be permitted if

1. the length of the ground path does not exceed 6 feet,
2. the circuit conductors contained in the flex do not have more than 20 amps overcurrent protection,
3. the fittings used are listed for grounding.

Comment: Section 250-91(b) listed flexible metal conduit, but the exception is more specific by naming both flexible metal conduit and flexible metallic tubing.

Reason (part 2 of the exception): There have been installations where, under fault conditions, the cross-sectional area of the flex is too small to carry the fault current without burning the flex in two and interrupting the ground path. Therefore, by limiting the branch circuit current overcurrent protection, the fault current on the flexible metal conduit is limited. Figure 10–24 illustrates flexible metal conduit installed for use as the equipment grounding conductor.

When the 20-amp limitation is placed on the branch circuit, it means that any circuit with overcurrent protection of more than 20 amps shall have an equipment grounding conductor installed inside or outside of the flexible metal

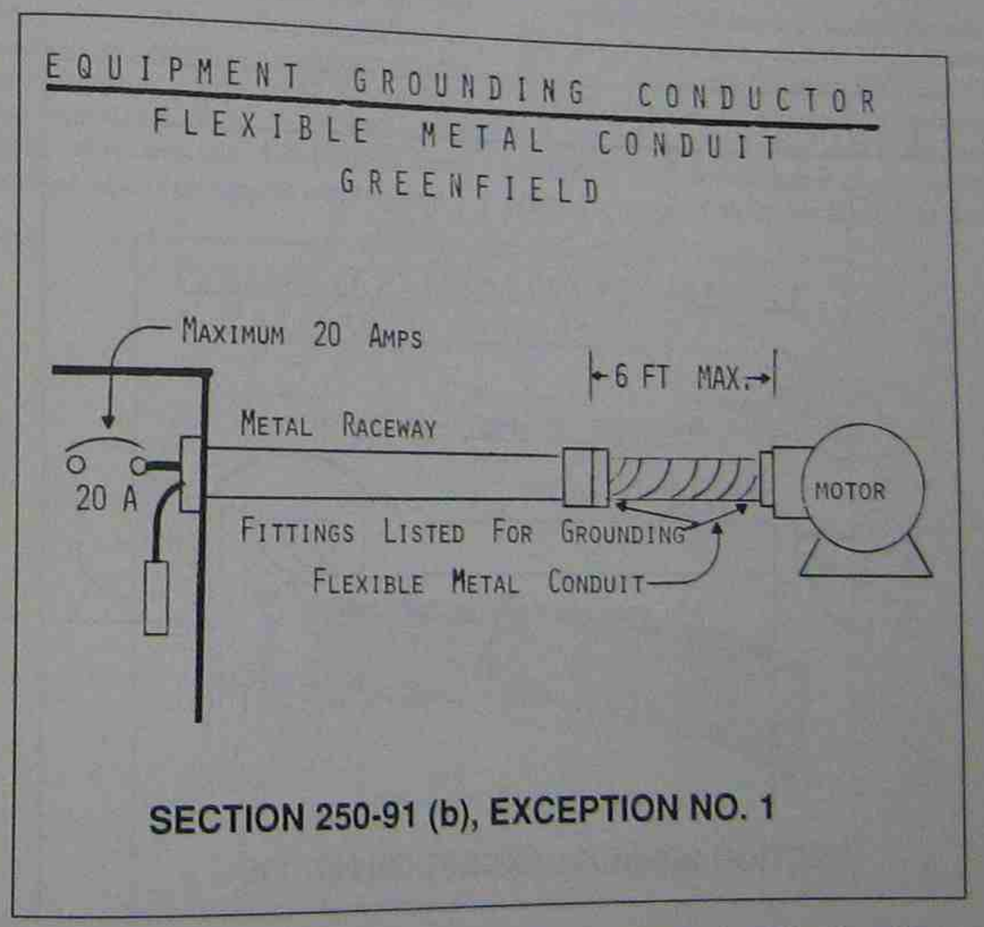


Fig. 10–24 An example of where flexible metal conduit is permitted to be used as the equipment grounding conductor.

conduit or flexible metallic tubing. Figure 10–25 illustrates the use of a 40-amp, branch circuit, overcurrent protective device and a motor with 6 feet or less of flexible metal conduit. The equipment grounding conductor must follow the flex and cannot be wrapped around the flex. Should the equipment grounding conductor be wrapped around the metal flex, theoretically it would cause transformer action.

Liquidtight Flexible Metal Conduit

Figure 10–26 illustrates Exception No. 2 of *Section 250-91(b)*. This exception is directed at liquidtight flexible metal conduit. Liquidtight flexible metal conduit is recognized for use as the equipment grounding conductor when all of the following limitations are met:

1. The trade size is 1-1/4 inch or smaller.
2. The length of the ground return path does not exceed 6 feet.
3. The conduit is terminated in fittings listed for grounding.
4. For 3/8- and 1/2-inch trade sizes, the overcurrent protection is limited to 20 amps or less.
5. For 3/4-, 1-, and 1-1/4-inch trade sizes, the overcurrent protection is limited to 30 amps.

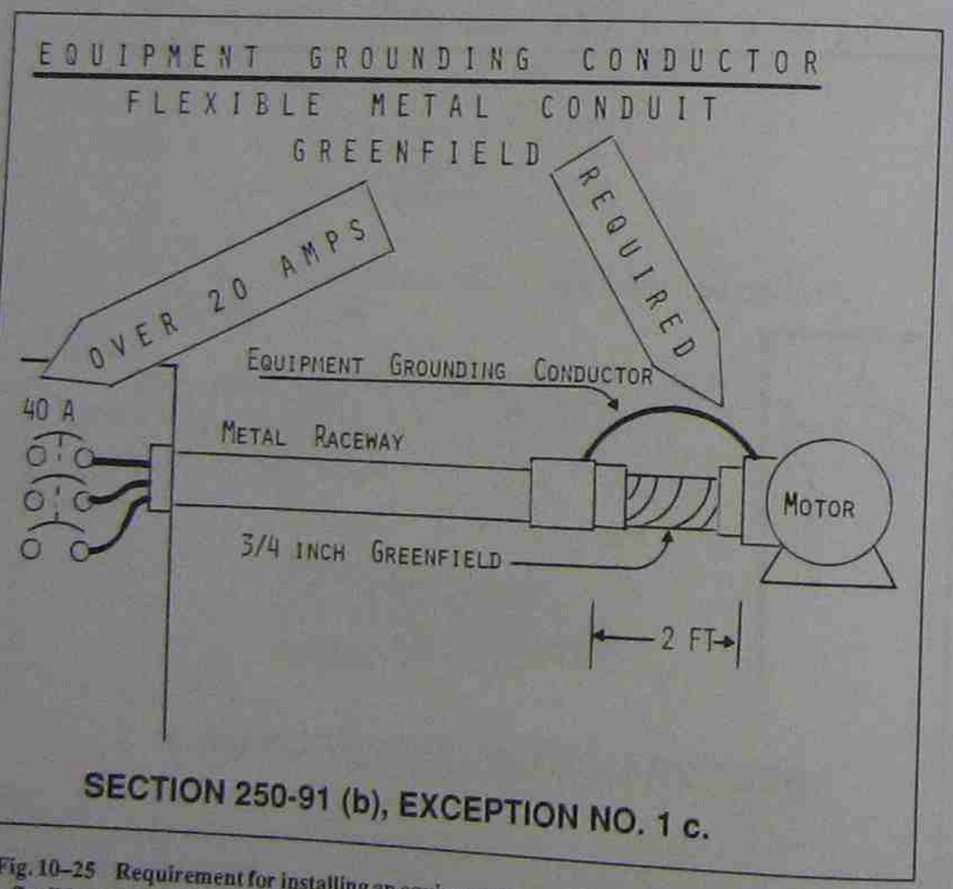


Fig. 10–25 Requirement for installing an equipment grounding conductor inside or outside a flexible metal conduit.

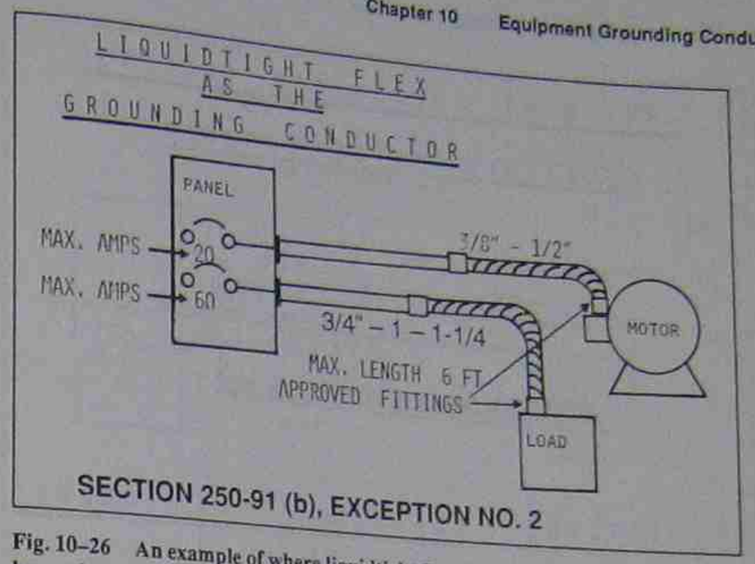


Fig. 10–26 An example of where liquidtight flexible metal conduit is permitted to be used as the equipment grounding conductor.

The 1-1/4-inch limitation also indicates that any time 1-1/2 inch or larger liquidtight flex is installed, an equipment grounding conductor shall be installed. Figure 10–27 illustrates the proper installation of the equipment bonding jumper, when required, with flexible metal conduit or liquidtight flexible metal conduit.

A further restriction is placed on the use of flexible metal conduit by *Section 350-5*, Exception No. 2, as illustrated in figure 10–28 (a). The exception requires that whenever equipment is installed requiring flexibility, and flexible metal conduit is used, an equipment grounding conductor is required to be installed. The same

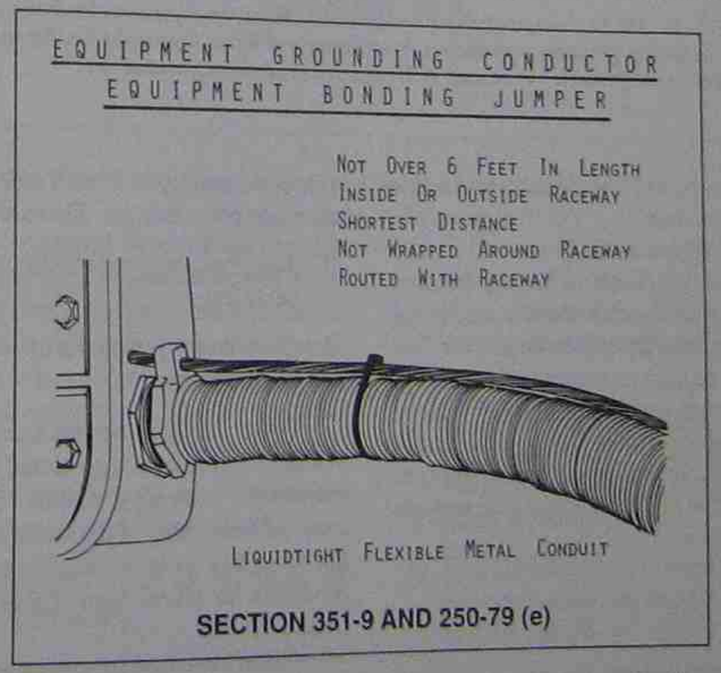
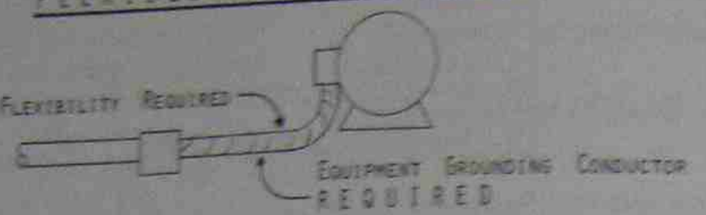


Fig. 10–27 An example of proper installation of an equipment bonding jumper with liquidtight flexible metal conduit.

EQUIPMENT GROUNDING CONDUCTOR

FLEXIBLE METAL CONDUIT

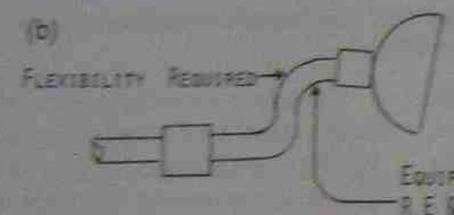
(a)



SECTION 350-5, EXCEPTION NO. 2

LIQUIDTIGHT FLEXIBLE METAL CONDUIT

(b)



SECTION 351-9, EXCEPTION NO. 2

Fig. 10–28 (a) An example of where flexible metal conduit is not permitted to be used as the equipment grounding conductor; (b) an example of where liquidtight flexible metal conduit is not permitted to be used as the equipment grounding conductor.

restriction is repeated for liquidtight flexible metal conduit in *Section 351-9*, Exception No. 2, as shown in figure 10–28 (b).

Comment: The Code is putting less and less confidence in flexible metal conduits for use as an equipment grounding conductor. The Code does not require an equipment grounding conductor in every installation of flexible metal conduit or flexible metallic tubing, but for practical application, an equipment grounding conductor installed in all flex would create an extra margin of safety.

Cable Tray

Section 250-91(b)(9) permits cable tray to be used as an equipment grounding conductor with two conditions from *Table 318-7(b)(2)* taken into consideration. These are:

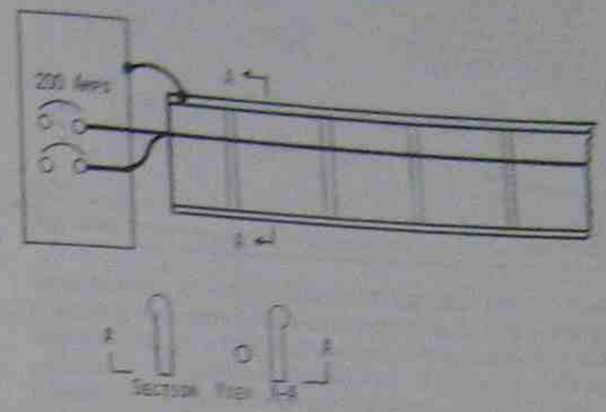
1. The cross-sectional area of the metal in the cable tray
2. Overcurrent protection of conductors in the cable tray

Figure 10–29 illustrates a cable tray, with a cable in the cable tray, protected by a 200-amp overcurrent protective device. The required cross-sectional area of the metal necessary for the cable tray to be an equipment grounding conductor is taken from *Table 318-7(b)(2)* (figure 10–30).

Cable trays used for equipment grounding conductors can be either steel or aluminum. The cross-sectional area of a ladder or trough-type

EQUIPMENT GROUNDING CONDUCTOR

CABLE TRAY



SECTION 318-7 (b) (2)

Fig. 10–29 Using cable tray as an equipment grounding conductor.

cable tray is calculated by using the two side rails of the cable tray. Where solid cable tray is used, the total cross-sectional area of the metal is used. Steel or aluminum cable tray systems are permitted to be used as equipment grounding conductors when all the following conditions are met:

1. The cable tray sections are identified for grounding purposes (figure 10–31).
2. The cable tray fittings are identified for grounding purposes.
3. The minimum cross-sectional area of the cable tray shall be in accordance with *Table 310–7(b)(2)*.
4. Cable tray sections and fittings for channel-type cable trays and cable trays of one-piece construction shall be legibly and durably marked with the cross-sectional area.
5. Ladder or trough-type cable tray sections and fittings shall be legibly and durably marked with the cross-sectional area of the metal in the side rails.
6. Cable tray sections, fittings, and connected raceways shall be bonded according to *Section 250-75*.
7. Bonding is permitted to be accomplished by the use of bolted mechanical connectors

Table 318-7(b) (2)
Metal Area Requirements for Cable Trays
Used as Equipment Grounding Conductors

Maximum Fuse Ampere Rating, Circuit Breaker Ampere Trip Setting, or Circuit Breaker Protective Relay Ampere Trip Setting for Ground-Fault Protection of any Cable Circuit in the Cable Tray System	Minimum Cross-Sectional Area of Metal* in Square Inches	
	Steel Cable Trays	Aluminum Cable Trays
60	0.20	0.20
100	0.40	0.20
200	0.70	0.20
400	1.00	0.40
600	1.50**	0.40
1000	—	0.60
1200	—	1.00
1600	—	1.50
2000	—	2.00**

Fig. 10–30 **Using *Table 318-7(b)(2)* to determine the required metal cross-sectional area of cable trays to be used as equipment grounding conductors.** Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright © 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

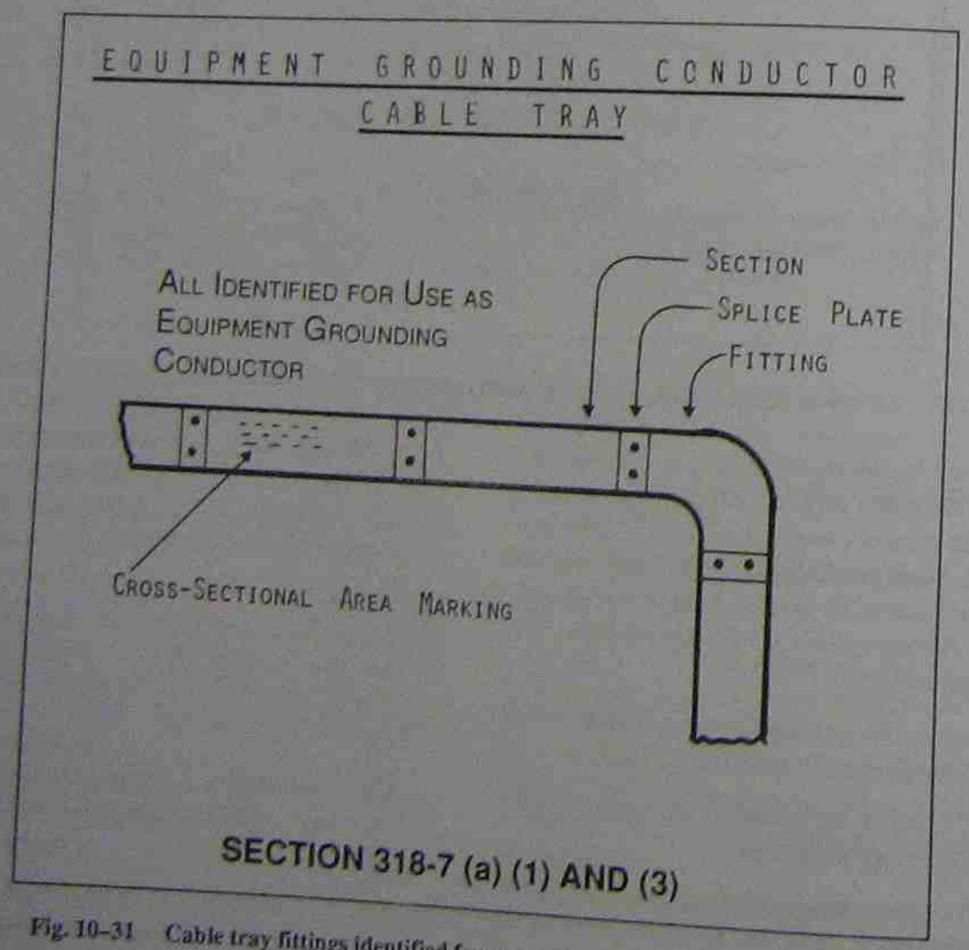


Fig. 10–31 **Cable tray fittings identified for use as equipment grounding conductors.**

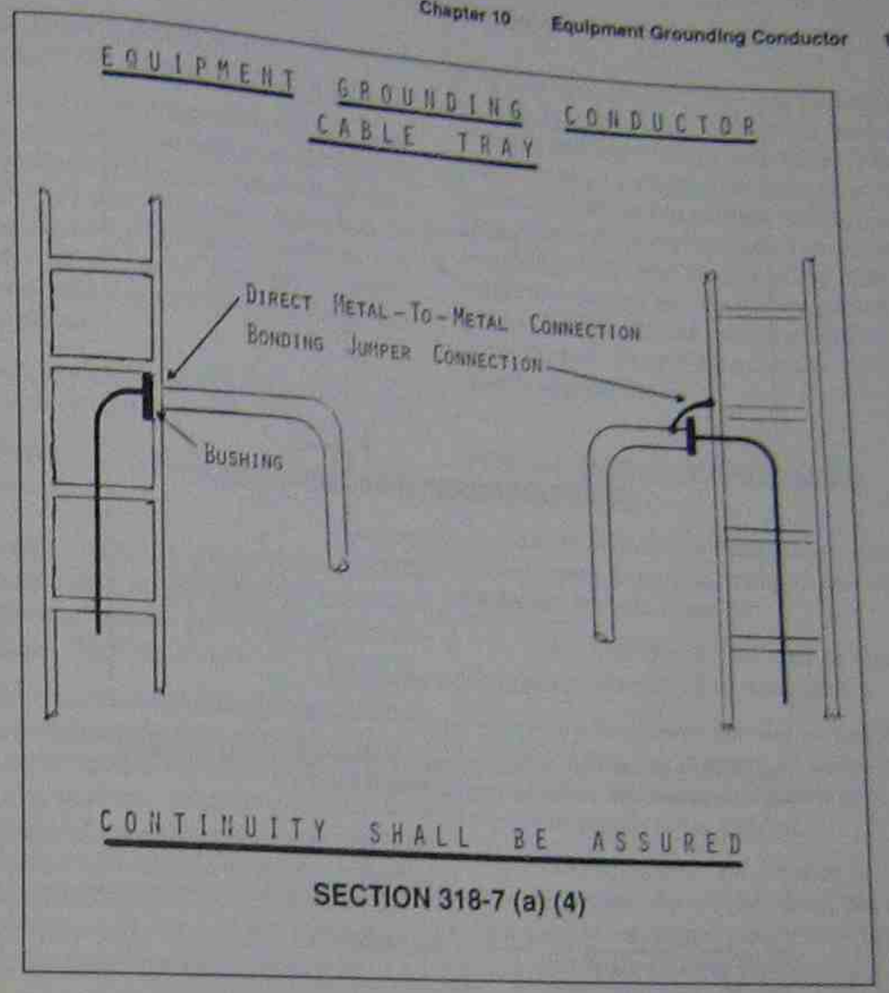


Fig. 10–32 **Assuring cable tray continuity.**

or bonding jumpers (figure 10–32, illustrated cable tray bonding).

8. When bonding jumpers are used, they are installed and sized according to *Section 250-79* (figure 10–32).

Steel cable trays shall not be used as equipment grounding conductors for circuits with ground-fault protection above 600 amps. Aluminum cable trays shall not be used as equipment grounding conductors for circuits with ground-fault protection above 2000 amps. These two requirements are listed in the notes to *Table 318-7(b)(2)*.

EARTH AS AN EQUIPMENT GROUNDING CONDUCTOR

NO! Section 250-91(c) permits the use of other grounding electrodes to supplement the equipment grounding conductor. The supplemental electrode does not take the place of the equipment grounding conductor. As shown in figure 10–33, if the equipment grounding conductor is not run to the lighting standard, the earth becomes the sole equipment grounding conductor. This is prohibited by *Sections 250-51* and *250-91(c)*.

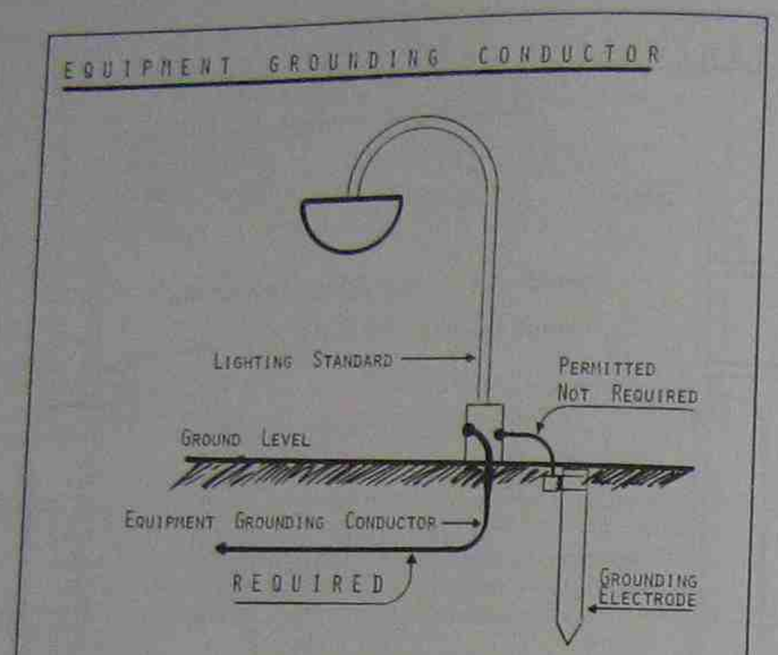


Fig. 10–33 A ground rod does not replace an equipment grounding conductor, but is permitted with an equipment grounding conductor.

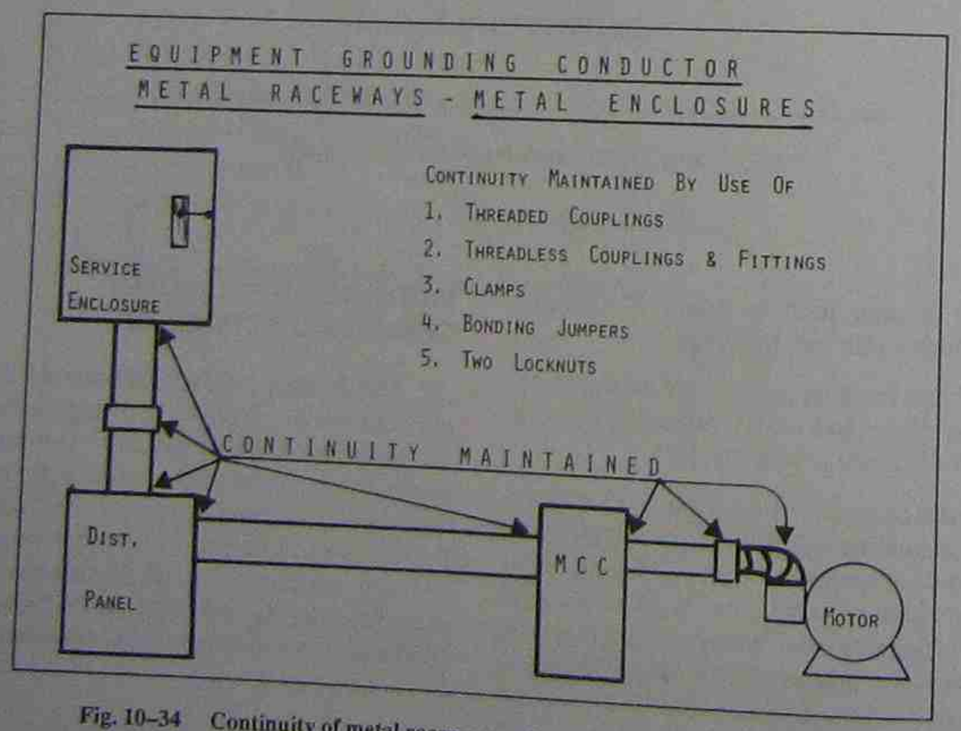


Fig. 10–34 Continuity of metal raceways and enclosures must be maintained.

EQUIPMENT GROUNDING CONDUCTOR CONNECTIONS

Figure 10–34 illustrates how all mechanical connections used to build a metallic raceway are depended upon to ensure continuity. *Section 250-92(c)(1)* sets down some regulations for making equipment grounding conductor connections when metal raceways or metal-sheathed cable is used as the equipment grounding conductor.

1. All joints and connections at fittings shall be madeup tight.
2. Suitable tools shall be used to makeup the fittings.
3. Paint, enamel, or similar coatings of nonconductive materials shall be removed at threads, contact points, and contact surfaces *(Section 250-75)*.

An exception permits the use of fittings that are designed to make removal of the nonconductive material unnecessary. These regulations also hold true when the metal raceway is not depended upon as the equipment grounding conductor and a separate equipment grounding conductor is installed in the metal raceway.

Section 250-113 requires the equipment grounding conductor connections to be

- Exothermic welding,
- Listed pressure connectors,
- Listed clamps,
- Or other listed means.
- No connections that depend solely on solder shall be used.

EQUIPMENT GROUNDING CONDUCTOR CONTINUITY

The continuity of the equipment grounding conductor must be maintained and is required by *Section 250-99*. Particular attention is given to situations where the equipment grounding conductor is part of a disconnecting means. This does not mean a switch, but something such as cord- and plug-connected equipment or draw-out switchgear, such as that used with 480 and high-voltage switchgear. When these conditions exist, the equipment grounding contact shall be the first to make and the last to break. Check the prongs or blades on an attachment plug. Note how the grounding blade is longer than any of the others. The grounding blade is the first to make contact and the last to break contact. Exceptions are made for very special applications.

SIZING EQUIPMENT GROUNDING CONDUCTORS

The regulations for calculating the size of the equipment grounding conductor are covered in *Section 250-95*. These are:

1. *Table 250-95* shall be used to size the equipment grounding conductor.
2. When conductors are run in parallel in more than one raceway, as permitted by *Section 310-4*, the equipment grounding conductor is run in parallel.
3. When conductors are adjusted in size to compensate for voltage drop, the equipment grounding conductor must be correspondingly adjusted in size.
4. Where more than one circuit is installed in a single raceway, one equipment grounding conductor can be installed in the raceway; it will be sized for the largest overcurrent device protecting conductors in the raceway.
5. An equipment grounding conductor not smaller than No. 18 copper is permitted for flexible cords when the flexible cord is protected at or over 20 amps.
6. The equipment grounding conductor is never required to be larger than the circuit conductors.

Note how the title of *Table 250-95* applies to both raceways and equipment. The left-hand column gives the key to the table. It indicates that the size of the equipment grounding

conductor is based on the overcurrent device next back on the line. The automatic overcurrent device can be either a set of fuses or a circuit breaker.

Figure 10–35 illustrates a system installed in nonmetallic raceway requiring the installation of several equipment grounding conductors. A copper conductor is used. Each panel, other than the service panel, has an isolated equipment grounding bus. The size of each equipment grounding conductor is read directly from *Table 250-95*, as illustrated in figure 10–36.

The feeder to the first panel is protected by a 300-amp breaker. Therefore, *Table 250-95* requires a No. 4 copper equipment grounding conductor.

Note the size of the equipment bonding jumper at the first panel. The 300-amp breaker at the service is the overcurrent protective device ahead of the equipment; therefore, its size is also read directly from *Table 250-95* and is No. 4 copper.

The second panel is protected by a 100-amp overcurrent protection device. *Table 250-95* shows that it requires a No. 8 copper conductor for the equipment grounding conductor and the bonding jumper in the second panel.

The branch circuit is protected by a 20-amp overcurrent device; therefore, *Table 250-95* requires a No. 12 copper conductor for the equipment grounding conductor.

Figure 10–37 illustrates the use of a 400-amp feeder installed in nonmetallic raceway,

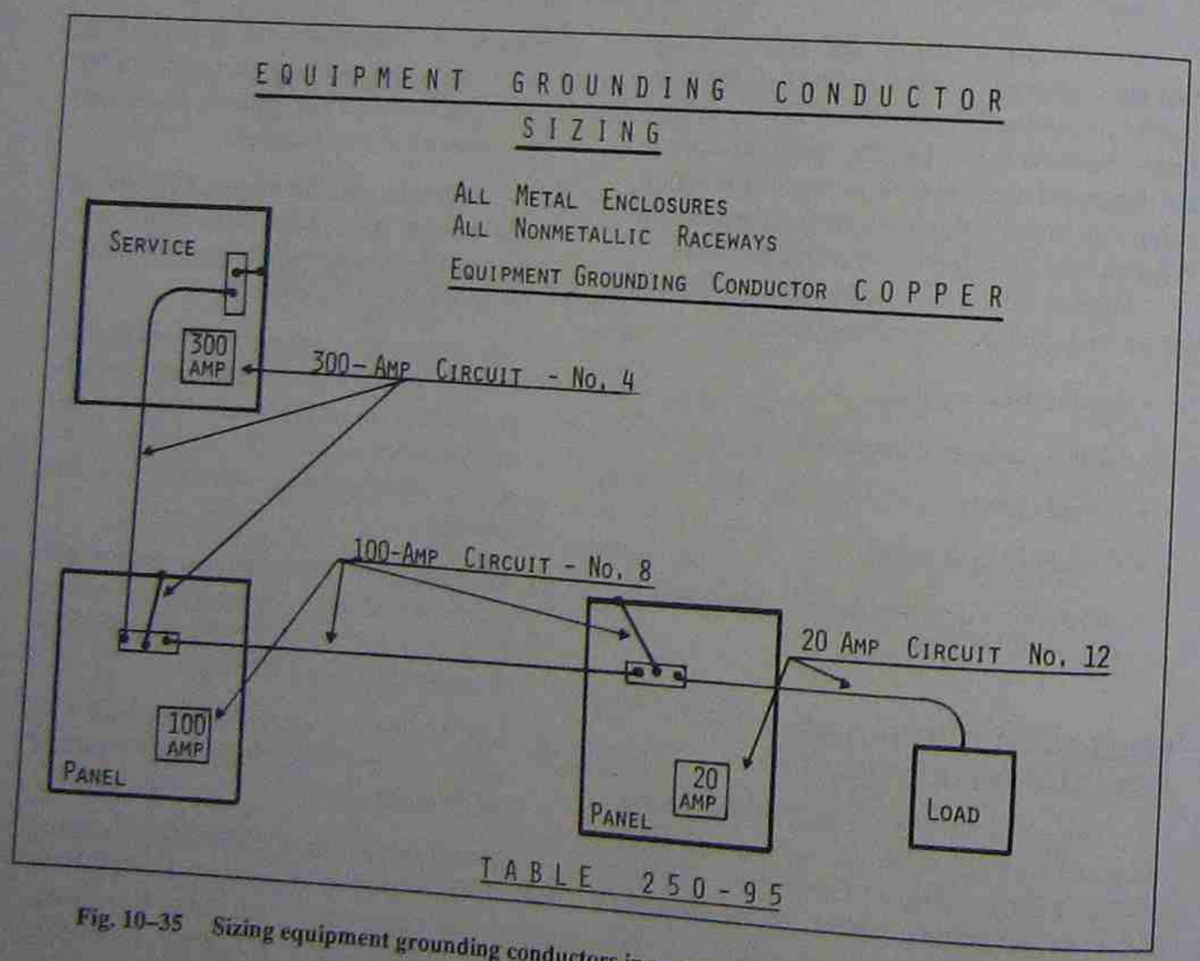


Fig. 10–35 Sizing equipment grounding conductors in nonmetallic raceway using *Table 250-95*.

Table 250-95. Minimum Size Equipment Grounding Conductors for Grounding Raceway and Equipment

Rating or Setting of Automatic Overcurrent Device in Circuit Ahead of Equipment, Conduit, etc., Not Exceeding (Amperes)	Size	
	Copper Wire No.	Aluminum or Copper-Clad Aluminum Wire No.*
15		
20	14	
30	12	12
	10	10
40		8
60	10	
100	10	8
	8	8
200		6
300	6	
400	4	4
	3	2
500		1
600	2	
800	1	1/0
	0	2/0
1000		3/0
1200	2/0	
1600	3/0	4/0
	4/0	250 MCM
2000		350 "
2500	250 MCM	
3000	350 "	400 "
	400 "	600 "
4000		600 "
5000	500 "	
6000	700 "	800 "
	800 "	1200 "
		1200 "

Fig. 10–36 Reading the sizes of the equipment grounding conductors from *Table-250-95*. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright © 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

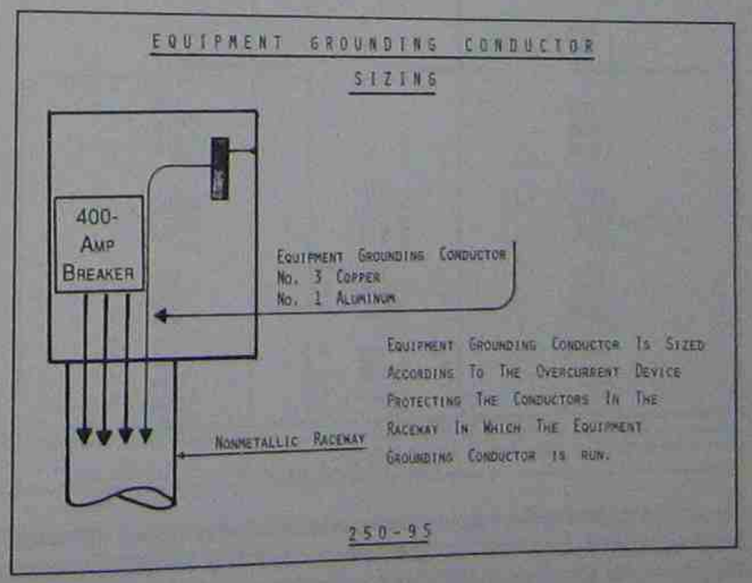


Fig. 10–37 Using a 400-amp breaker in nonmetallic raceway, which requires an equipment grounding conductor.

which requires an equipment grounding conductor. An equipment grounding bus is illustrated in the panel with the panel bonded to the equipment grounding bus. It is not a neutral bus and is not bonded to the neutral bus. Either copper or aluminum can be used for the equipment grounding conductor. The size of the equipment grounding conductor is read directly from *Table 250-95* (figure 10–38). If copper is used, it will be a No. 3 copper conductor; if aluminum is used, it will be a No. 1 aluminum conductor.

Figure 10–39 is based on the second paragraph of *Section 250-95* for sizing the equipment grounding conductor when run with parallel conductors, as permitted by *Section 310-4*.

1. The equipment grounding conductor, when installed, shall be run in parallel.
2. The minimum size of the equipment grounding conductors is based on the overcurrent device protecting the circuit conductors in the raceways.
3. *Table 250-95* is used for sizing equipment grounding conductors.

Therefore, the size of the equipment grounding conductor, read directly from *Table 250-95* (figure 10–40), is No. 3 copper.

Table 250-95. Minimum Size Equipment Grounding Conductors for Grounding Raceway and Equipment

Rating or Setting of Automatic Overcurrent Device in Circuit Ahead of Equipment, Conduit, etc., Not Exceeding (Amperes)	Size	
	Copper Wire No.	Aluminum or Copper-Clad Aluminum Wire No.*
15	14	12
20	12	10
30	10	8
40	10	8
60	10	8
100	8	6
200	6	4
300	4	2
→ 400	→ 3	→ 1
500	2	1/0
600	1	2/0
800	0	3/0
1000	2/0	4/0
1200	3/0	250 MCM
1600	4/0	350 "
2000	250 MCM	400 "
2500	350 "	600 "
3000	400 "	600 "
4000	500 "	800 "
5000	700 "	1200 "
6000	800 "	1200 "

* See installation restrictions in Section 250-92(a).

Fig. 10–38 Sizing the equipment grounding conductor when a 400-amp breaker is used. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright © 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

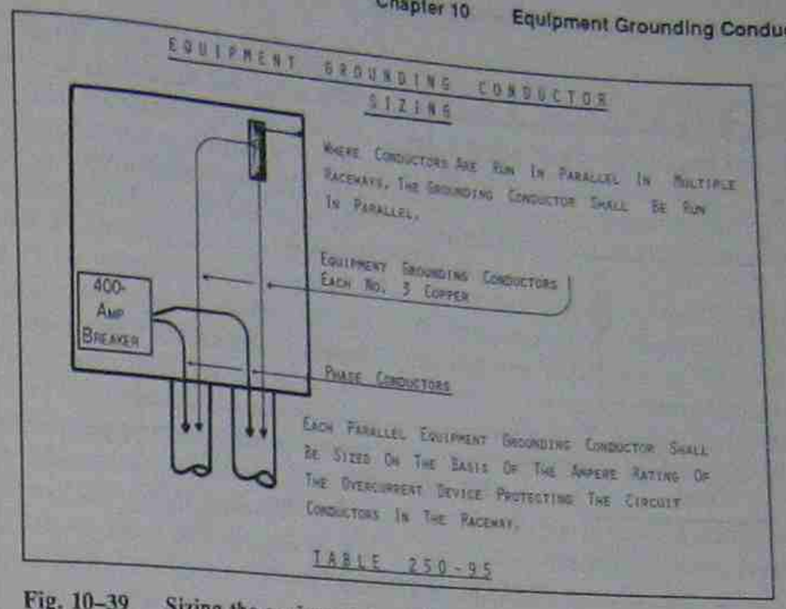


Fig. 10–39 Sizing the equipment grounding conductor when parallel feeder is installed in parallel nonmetallic conduits.

Table 250-95. Minimum Size Equipment Grounding Conductors for Grounding Raceway and Equipment

Rating or Setting of Automatic Overcurrent Device in Circuit Ahead of Equipment, Conduit, etc., Not Exceeding (Amperes)	Size	
	Copper Wire No.	Aluminum or Copper-Clad Aluminum Wire No.*
15	14	12
20	12	10
30	10	8
40	10	8
60	10	8
100	8	6
200	6	4
300	4	2
→ 400	→ 3	→ 1
500	2	1/0
600	1	2/0
800	0	3/0
1000	2/0	4/0
1200	3/0	250 MCM
1600	4/0	350 "
2000	250 MCM	400 "
2500	350 "	600 "
3000	400 "	600 "
4000	500 "	800 "
5000	700 "	1200 "
6000	800 "	1200 "

* See installation restrictions in Section 250-92(a).

Fig. 10–40 Using *Table 250-95* to select No. 3 copper as the equipment grounding conductor. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright © 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

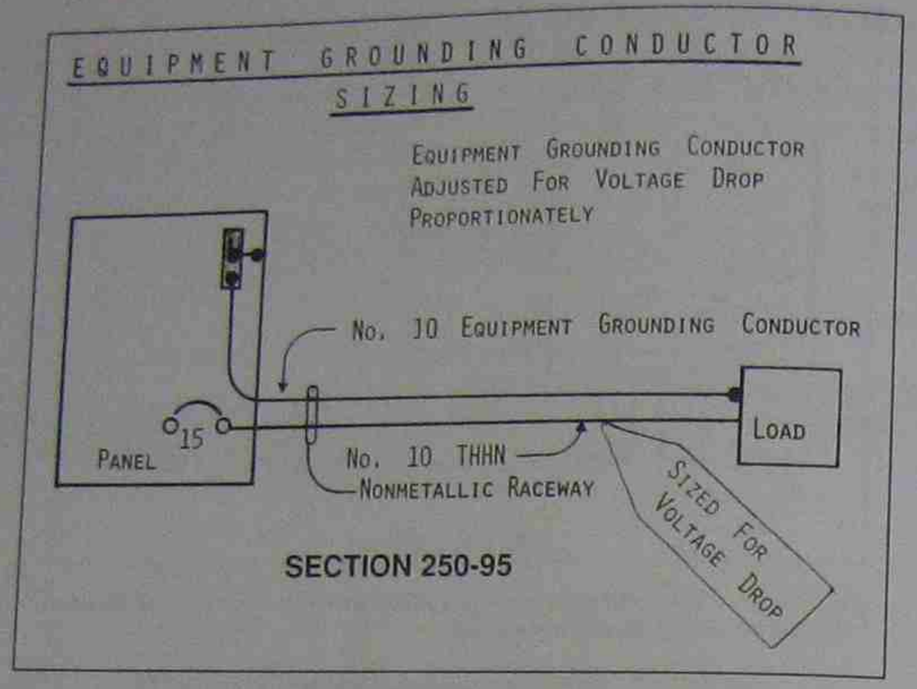


Fig. 10–41 The size of the equipment grounding conductor is adjusted for voltage drop.

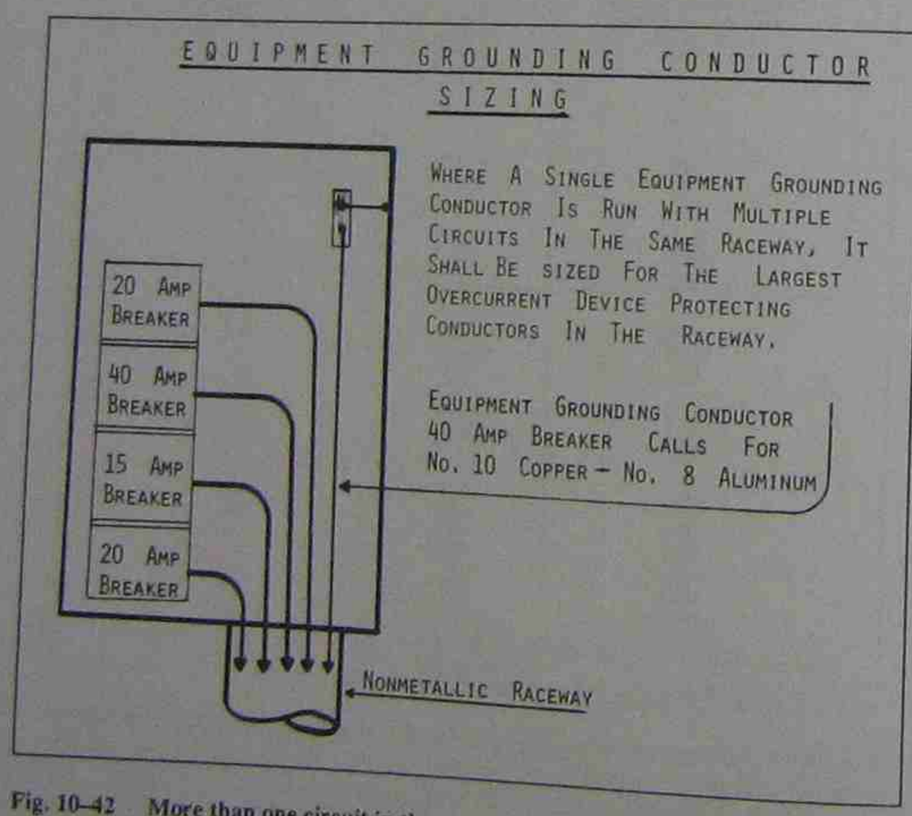


Fig. 10–42 More than one circuit in the same raceway requires sizing the equipment grounding conductor according to the largest overcurrent protective device.

Table 250-95 requires a No. 3 copper conductor for a circuit backed up with a 400-amp breaker. The conductors in each conduit are backed up with a 400-amp breaker. Therefore, two No. 3 copper equipment grounding conductors are required, one in each raceway.

Figure 10–41 illustrates the requirement in *Section 250-95* for voltage drop. The reason a larger-size conductor is used to reduce voltage drop is that the larger conductor has a lower resistance. Therefore, when the size of the circuit conductors is increased for voltage drop, the size of the equipment grounding conductor is increased proportionally, thereby reducing the impedance of the ground fault path.

Figure 10–42 illustrates the use of one equipment grounding conductor with multiple circuits installed in the same raceway, as required by *Section 250-95*. It is not anticipated that a ground fault will happen simultaneously on all circuits in the raceway at the same time. Therefore, the equipment grounding conductor is sized according to the largest overcurrent device.

In the illustration, the 40-amp breaker is the largest overcurrent protective device protecting any conductor in the one raceway. Therefore, the size of the equipment grounding conductor is read directly from *Table 250-95* (figure 10–43). It would be No. 10 copper or No. 8 aluminum.

Figure 10–44 illustrates a circuit protected by a 70-amp overcurrent protective device, with a copper equipment grounding conductor

Table 250-95. Minimum Size Equipment Grounding Conductors for Grounding Raceway and Equipment

Rating or Setting of Automatic Overcurrent Device in Circuit Ahead of Equipment, Conduit, etc., Not Exceeding (Amperes)	Size	
	Copper Wire No.	Aluminum or Copper-Clad Aluminum Wire No.*
15	14	12
20	12	10
30	10	8
→ 40	→ 10	→ 8
60	10	8
100	8	6
200	6	4
300	4	2
400	3	1
500	2	1/0
600	1	2/0
800	0	3/0
1000	2/0	4/0
1200	3/0	250 MCM
1600	4/0	350 "
2000	250 MCM	400 "
2500	350 "	600 "
3000	400 "	600 "
4000	500 "	800 "
5000	700 "	1200 "
6000	800 "	1200 "

* See installation restrictions in Section 250-92(a)

Fig. 10–43 Using *Table 250-95* to select No. 10 copper or No. 8 aluminum as the equipment grounding conductor. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright © 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

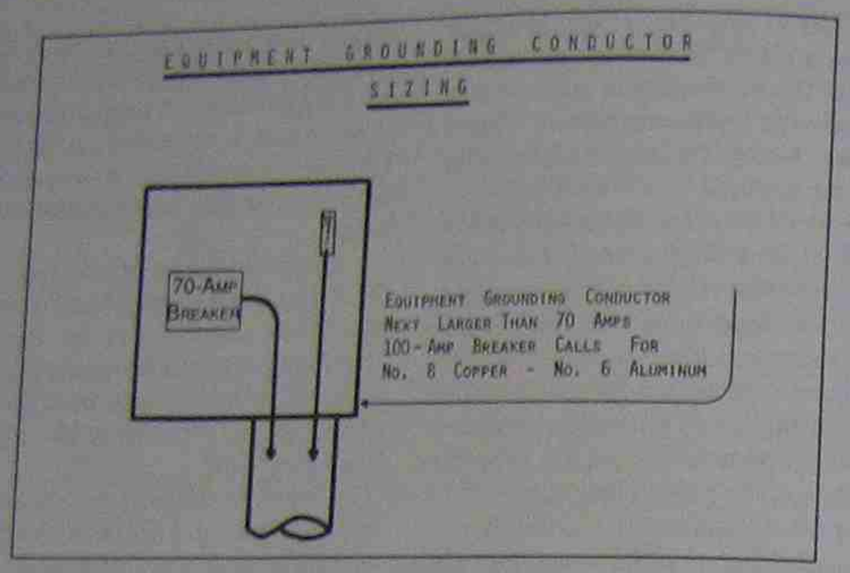


Fig. 10–44 Sizing an equipment grounding conductor protected by a 70-amp breaker. The next larger size breaker is required.

Table 250-95. Minimum Size Equipment Grounding Conductors for Grounding Raceway and Equipment

Rating or Setting of Automatic Overcurrent Device in Circuit Ahead of Equipment, Conduit, etc., Not Exceeding (Amperes)	Size: Copper Wire No.	Size: Aluminum or Copper-Clad Aluminum Wire No.*
15	14	12
20	12	10
30	10	8
40	10	8
60	10	8
NEXT LARGER 70 AMPS → 100	→ 8	→ 6
200	6	4
300	4	2
400	3	1
500	2	1/0
600	1	2/0
800	0	3/0
1000	2/0	4/0
1200	3/0	250 MCM
1600	4/0	350 "
2000	250 MCM	400 "
2500	350 "	600 "
3000	400 "	600 "
4000	500 "	800 "
5000	700 "	1200 "
6000	800 "	1200 "

* See installation restrictions in Section 250-92(a)

Fig. 10–45 Using *Table 250-95* to size the equipment grounding conductor. The next larger size is a 100-amp breaker, which requires No. 8 copper or No. 6 aluminum. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright © 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

When checking *Table 250-95*, there is no 70-amp rating listed. Therefore, as indicated at the top of *Table 250-95* (figure 10–45), "Not Exceeding (Amperes)," the next larger size equipment grounding conductor is required—No. 8 copper.

Figure 10–46 illustrates a situation where *Table 250-95* would require a No. 10 copper or No. 6 aluminum conductor for the 50-amp breaker. But because the circuit's overcurrent protective device takes into consideration the starting current of the motor, the equipment grounding conductor need not be larger than the circuit conductor (No. 14).

When an insulated conductor is installed for the equipment grounding conductor in a metal raceway (figure 10–47), or when it is part of a metal-covered cable assembly, all joints

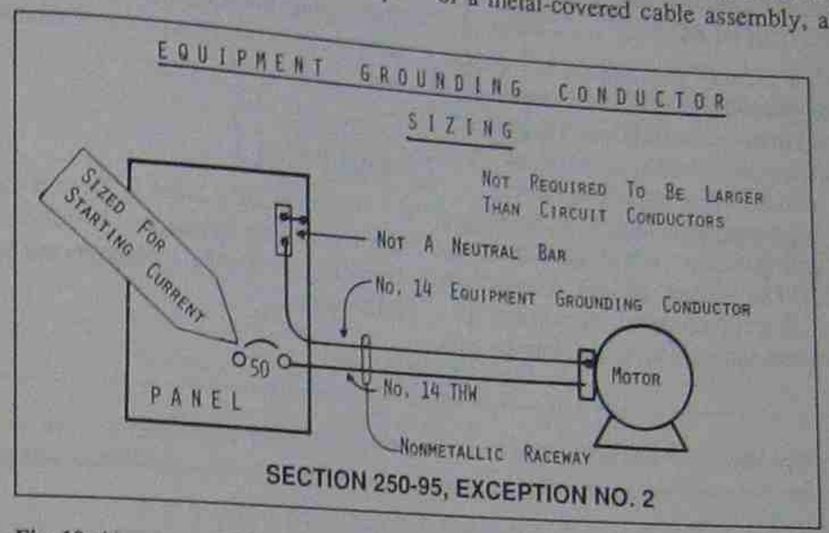


Fig. 10–46 An exception where the equipment grounding conductor is not required to be larger than the circuit conductors.

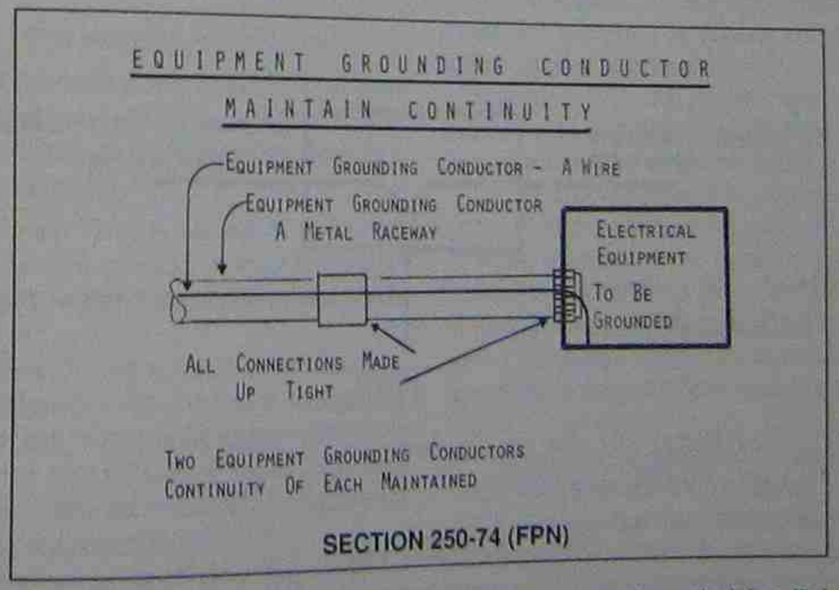


Fig. 10–47 Continuity of a metal raceway must still be maintained when a wire is installed for the equipment grounding conductor.

and fittings of the metal raceway, cable, and enclosure shall be madeup as if the raceway or enclosure is the primary equipment grounding conductor. This is specifically covered in the Fine Print Note to *Section 250-74* as a point of information.

EQUIPMENT GROUNDING CONDUCTOR IN BOXES

Section 250-114 pays special attention to equipment grounding conductors installed in metal boxes or nonmetallic boxes. The first part of this section covers both types of boxes. Then a special section is devoted to each type.

The uninterrupted continuity of the equipment grounding conductor is also protected by *Section 250-114* (figure 10–48). Very often when a building is remodeled, receptacles, fixtures, or other devices are removed from the box that feeds them. Therefore, the arrangement of the equipment grounding conductor connections in the feed box shall be such that when one of these items is removed, the continuity of the equipment grounding conductor will not be interrupted.

Reason: If the splice is made on the receptacle or on the fixture and the receptacle or fixture is removed, an open circuit could result, interrupting the equipment grounding conductor path and creating a potential electrical hazard.

Metal Boxes

Section 250-114(a) is directed at equipment grounding conductors installed in metal boxes (figure 10–49). It contains the following information:

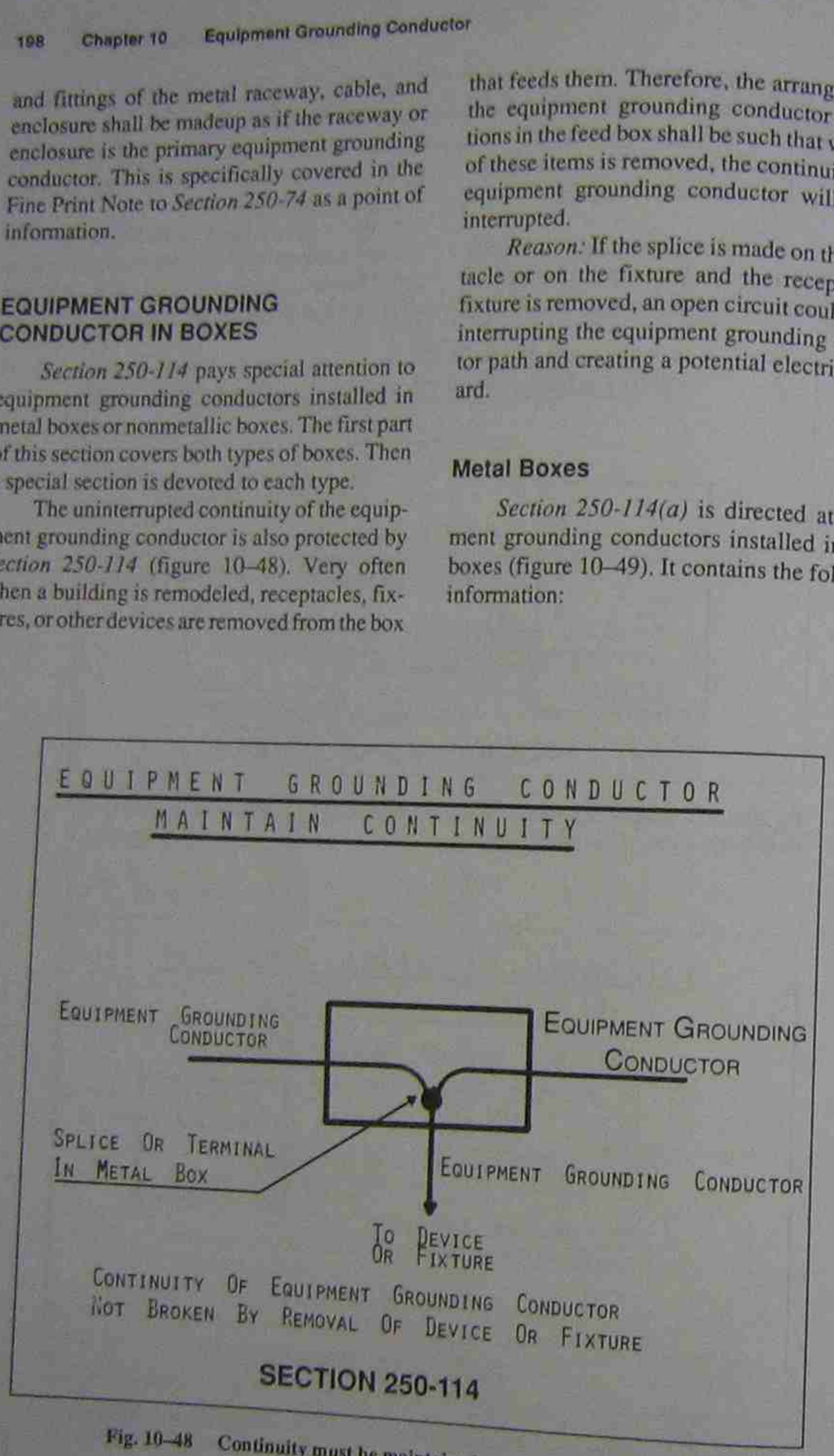


Fig. 10–48 Continuity must be maintained at pull or junction boxes.

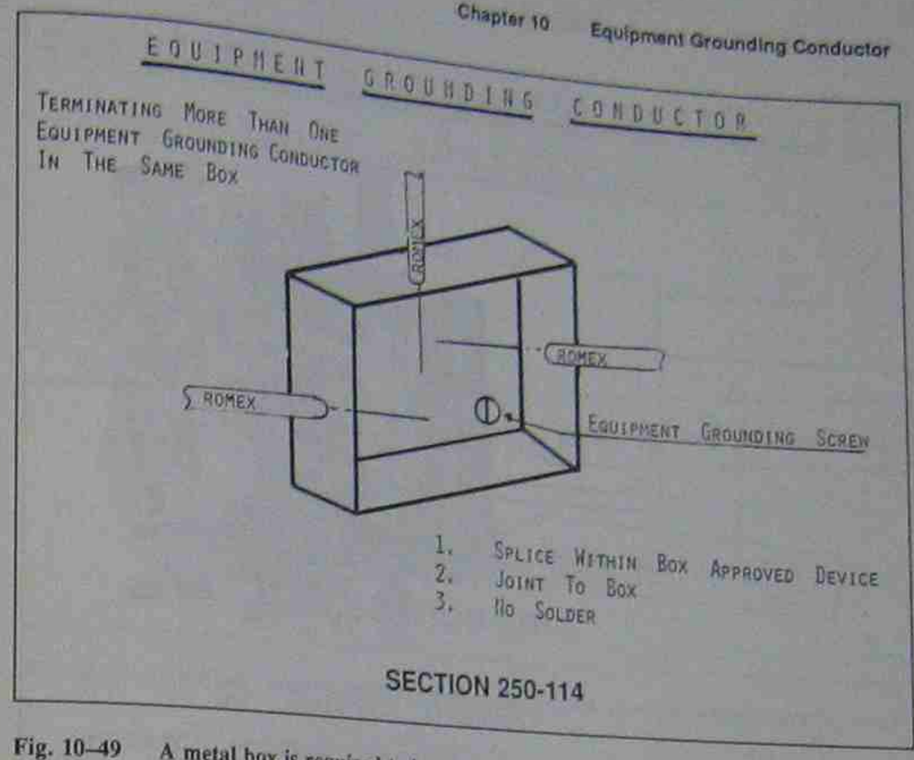


Fig. 10–49 A metal box is required to have a means of terminating and connecting equipment grounding conductors.

1. A connection is required between the equipment grounding conductor and the box.
2. The connection can be made with
   a. a grounding screw, used for no other purpose,
   b. a listed grounding device, such as a connector.

Comment: This is backed up under construction specifications for boxes in *Article 370*. The equipment grounding screw is illustrated in figure 10–48.

Section 370-20(d) is also directed at metal boxes designed to be used with nonmetallic raceways and nonmetallic cable systems. It requires the box to have provisions manufactured into the box for connecting the equipment grounding conductor.

When the equipment grounding conductor is connected to the screw in the metal box, it serves two purposes. First, it makes a splice point for equipment grounding conductors passing through the box. Second, it provides a means to ground the box and maintains the metal box enclosing or serving the device or fixture at ground potential.

Section 250-114 permits splices to be made in the equipment grounding conductor in boxes, without the conductor being insulated.

CAUTION: Although a splice is permitted in the equipment grounding conductor without it being insulated, care must be used when making an installation in a box that is very crowded. There are hot conductors in the box, such as those on a receptacle, that could come in contact with the grounded conductor and cause a fault.

Figure 10–50 illustrates the proper installation with a metal box, nonmetallic sheathed cable, and an equipment grounding conductor in the metal box. The connections are made so the metal box is grounded, and the equipment grounding conductor's continuity and the

Fig. 10–50 Proper termination of an equipment grounding conductor and a grounded conductor in a device box.

grounded conductor's continuity would not be broken, should the receptacle be removed. A connection is made to the grounding screw provided in the box and a pigtail splice is made with a listed splicing device.

Nonmetallic Boxes

Attention is also given to nonmetallic boxes. *Section 250-114(b)* requires the nonmetallic box to have conductor arrangements so that a connection can be made to any fitting or device in the box required to be grounded. *Section 370-3* requires that when metal raceway or metal-sheathed cable is attached to a nonmetallic box by a threaded entry, bonding provisions shall be provided for the metal raceway or metal-sheathed cable.

Where the metal raceway is used as the equipment grounding conductor, the grounding path is interrupted and something must be done to maintain continuity when it passes through a nonmetallic box (figure 10–51). Metal raceway is only permitted to be used with nonmetallic boxes when the box is 100 cubic inches or larger. A 5-inch square and 4-inch-deep box would be 100 cubic inches.

Figure 10–52 illustrates the size of the bonding jumper to be used. The overcurrent device next back protecting the circuit conductors passing through the box is used to calculate the size of the equipment grounding conductor. In this case the conductors are protected with a 60-amp breaker. Therefore, the size of the bonding jumper is taken directly from *Table 250-95* and is No. 10 copper or No. 8 aluminum.

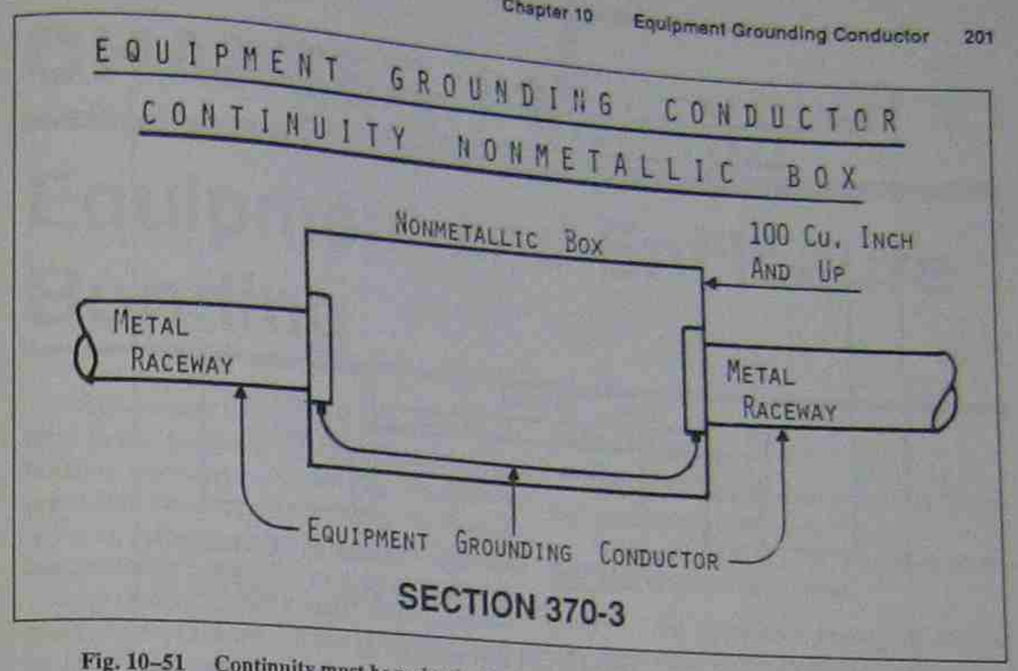


Fig. 10–51 Continuity must be maintained when using metal raceways with nonmetallic boxes.

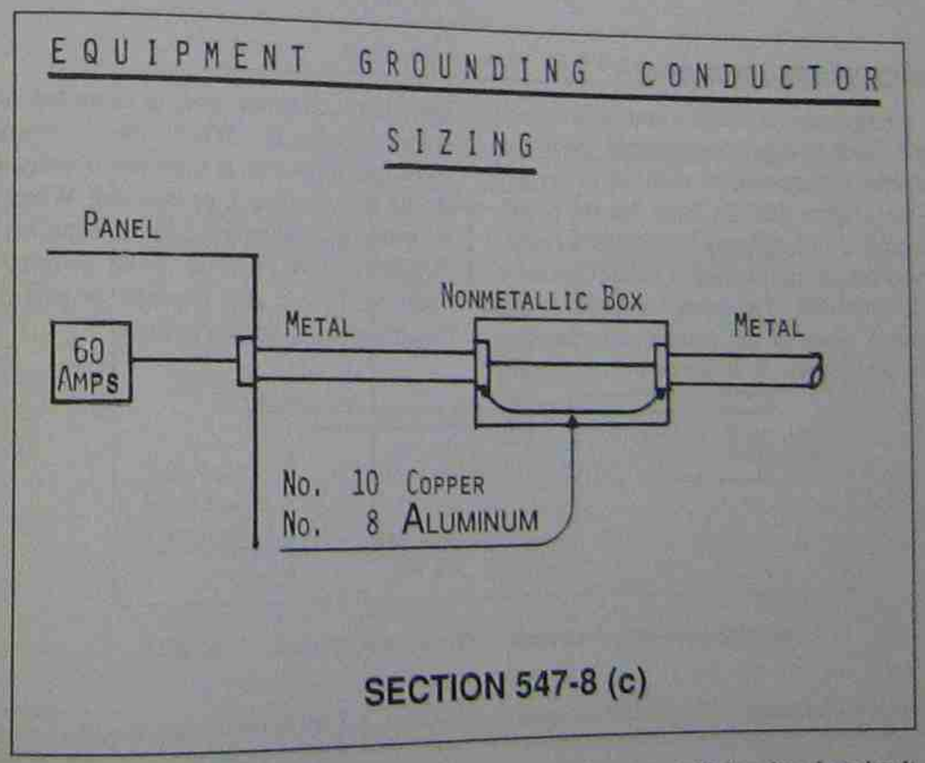


Fig. 10–52 Sizing the equipment grounding conductor through a nonmetallic box, based on circuit overcurrent protection.

CHAPTER 11

Equipment and Enclosure Bonding

This chapter focuses on bonding as it functions in the grounding system. The equipment bonding jumpers maintain the equipment grounding conductor's continuity, so there is never an open circuit in the equipment grounding conductor's path. The main bonding jumper was covered in chapter 9, and it has its particular purpose. Now the main focus of this chapter is on the equipment bonding jumper and the important part it plays in the overall grounding system.

DEFINITIONS

Article 100 lists five definitions for "Bonding" and "Bonding Jumpers."

Bonding (figure 11–2), according to *Article 100*, is defined as follows:

Quote – "The permanent joining of metallic parts to form an electrically conductive path which will assure electrical continuity and the capacity to conduct safely any current likely to be imposed."*

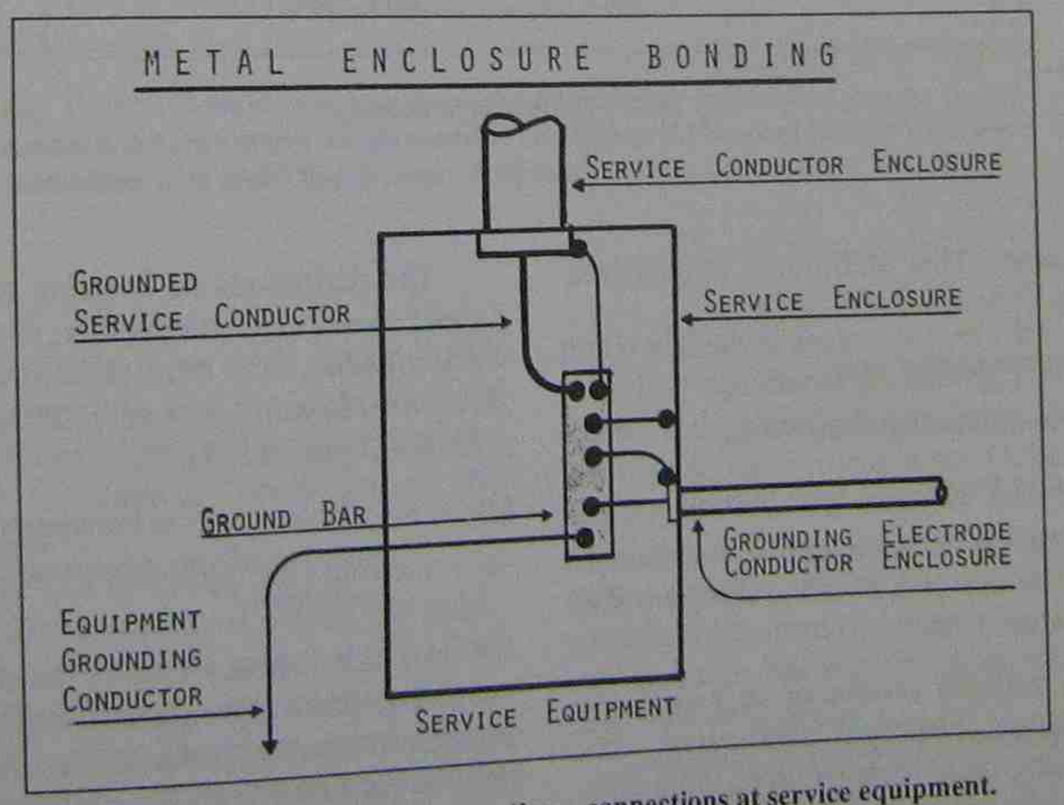


Fig. 11–1 Metal enclosure bonding—connections at service equipment.

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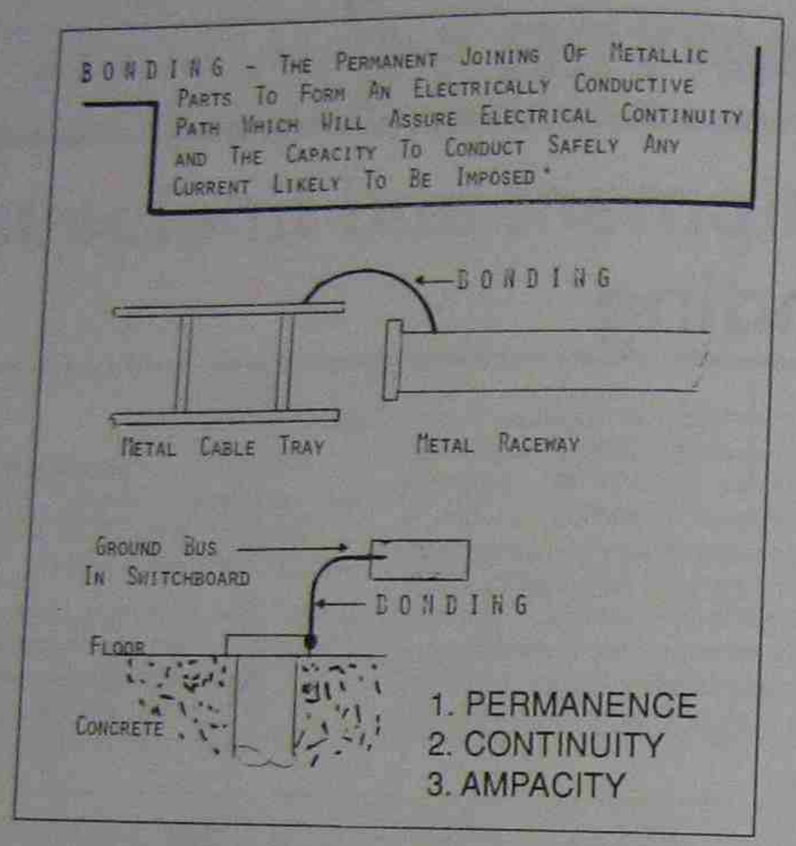

Fig. 11–2 Definition of *bonding*.

Comment: This definition emphasizes three things. These are:

1. Permanent connection
2. Positive continuity at all times
3. Ampacity to conduct fault current

Bonding, as defined above, is accomplished by the use of a *Bonding Jumper*, also defined in *Article 100*.

Quote – "A reliable conductor to assure the required electrical conductivity between metal parts required to be electrically connected."*

The definitions of *bonding* and *bonding jumper* sound very much alike; the two things work together. The third definition is for the *Equipment Bonding Jumper*, also found in *Article 100* (figure 11–3).

Quote – "The connection between two or more portions of the equipment grounding conductor."*

A metal raceway may be used as the primary equipment grounding conductor, and equipment bonding jumpers are used to maintain the continuity and ampacity of the equipment grounding conductor.

Figure 11–3 illustrates two installations requiring the use of an equipment bonding jumper. Figure 11–3 (a) shows that without the equipment bonding jumper, there is no connection, no continuity, and no ampacity to carry

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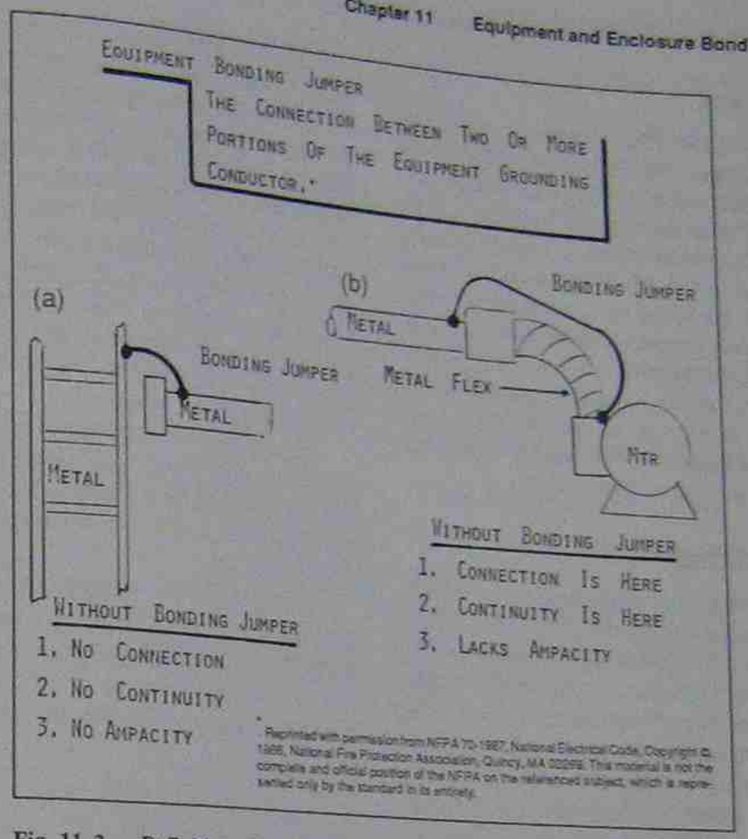


Fig. 11–3 Definition of *equipment bonding jumper:* (a) bonding jumper is sole connection between two metals to assure continuity; (b) bonding jumper is parallel connection with metal flex to assure continuity.

fault current. There is an open circuit in the equipment grounding circuit. Therefore, the Code requires an equipment bonding jumper to be installed to maintain continuity of the grounding path.

With the use of metal flex, as shown in figure 11–3 (b), the circuit is closed, the continuity is there, but the cross-sectional area of the metal in the flex is not always large enough to carry the fault current. Therefore, an equipment bonding jumper is needed to assure ampacity for possible fault current.

The equipment bonding jumpers in figure 11–3 are insurance connections. For example, an individual may buy hospitalization insurance and have high hopes of never using it. The bonding jumper is also installed with high hopes that it will never have to be used. It helps create a healthy equipment grounding system called "safe." If the electrical installation always stays healthy and lucky, there might not be a need for equipment bonding jumpers and equipment grounding. But when an electrical installation is afflicted with an ailment such as a fault, or when it has an accident and is hit by lightning or a high current surge, the equipment bonding jumper insurance pays off.

Bonding is looked at in three different situations in this chapter. These are:

1. Service—equipment and enclosures
2. Other than service—equipment and enclosures
3. Multiple grounding electrode systems

MATERIALS

Section 250-79(a) permits the equipment bonding jumper to be copper or another corrosion-resistant material. Although this permits the use of other than copper conductors, there are specific places where a copper bonding jumper is required. Metal fittings listed for the purpose are permitted for use in place of equipment bonding jumpers in limited installations. *Section 250-91(b)* permits the equipment bonding jumper, which is part of the equipment grounding conductor, to be insulated, bare, stranded, or solid. However, the bare conductor cannot be used for all installations.

CONNECTIONS

All connection requirements for equipment grounding conductors apply to equipment bonding jumpers. Once again, *Section 250-92(c)(1)* comes into play. It requires all bonding jumper connections for joints and fittings to be madeup tight using suitable tools. *Section 250-75* requires the removal of nonconductive paint, enamel, or similar coatings. *Section 250-113* requires the equipment bonding jumper connection to be made by means of any of the following:

1. Exothermic welding
2. Listed pressure connectors
3. Listed clamps
4. Other listed means
5. Connections that depend solely on solder not permitted

BONDING AT SERVICE EQUIPMENT

The requirements for equipment and enclosure bonding on the supply (line) side of the service equipment are more stringent than some of the requirements for bonding on the load side of the service equipment. For example, locknuts and bushings are not depended upon to assure continuity of the grounding system on the supply side of the service, but on the load side of the service equipment they are permitted under certain conditions.

There is good reason for this extra precaution. The only overcurrent protection for the service is the overcurrent protection on the primary side of the utility company transformer. This is to protect the utility company transformer and not the many services that will be connected to the secondary of the transformer. This overcurrent protection offers no protection for the service equipment or anything on the line side of the service equipment. Therefore, all grounding connections are made extra sure with the intent of trying to burn the fault clear before a more serious fault takes place.

Figure 11–4 illustrates some of the various grounding conductors discussed up to this point. It also shows the location and identification of line side and load side equipment bonding jumpers.

Section 250-71(a) requires the noncurrent-carrying metal parts of the service equipment to be effectively bonded together, as illustrated in figure 11–5, and lists three specific parts of the service equipment where this shall occur. These are:

1. Conductor enclosure
2. Equipment enclosure
3. Grounding electrode conductor enclosure

Section 250-55 gives an exception to this requirement for underground service cable. This is a bit unusual for the exception not to be a separate part of the section. *Section 250-55* has to do with an underground installation of metal-clad cable and an underground system. This does not apply to metal-clad cable installed overhead in free air.

Cable tray is listed separately from metal raceways used for service-entrance conductors; its use as an equipment grounding conductor was covered in chapter 10 of this text. However, in order to keep the continuity of cable tray as an equipment grounding conductor, equipment bonding jumpers are often needed. The metal service raceway for which equipment bonding jumpers are required are those given in *Section 230-43*, which lists the wiring methods permitted to be used as raceways for the service-entrance conductor. Metal raceways permitted by *Section 230-43* are the following:

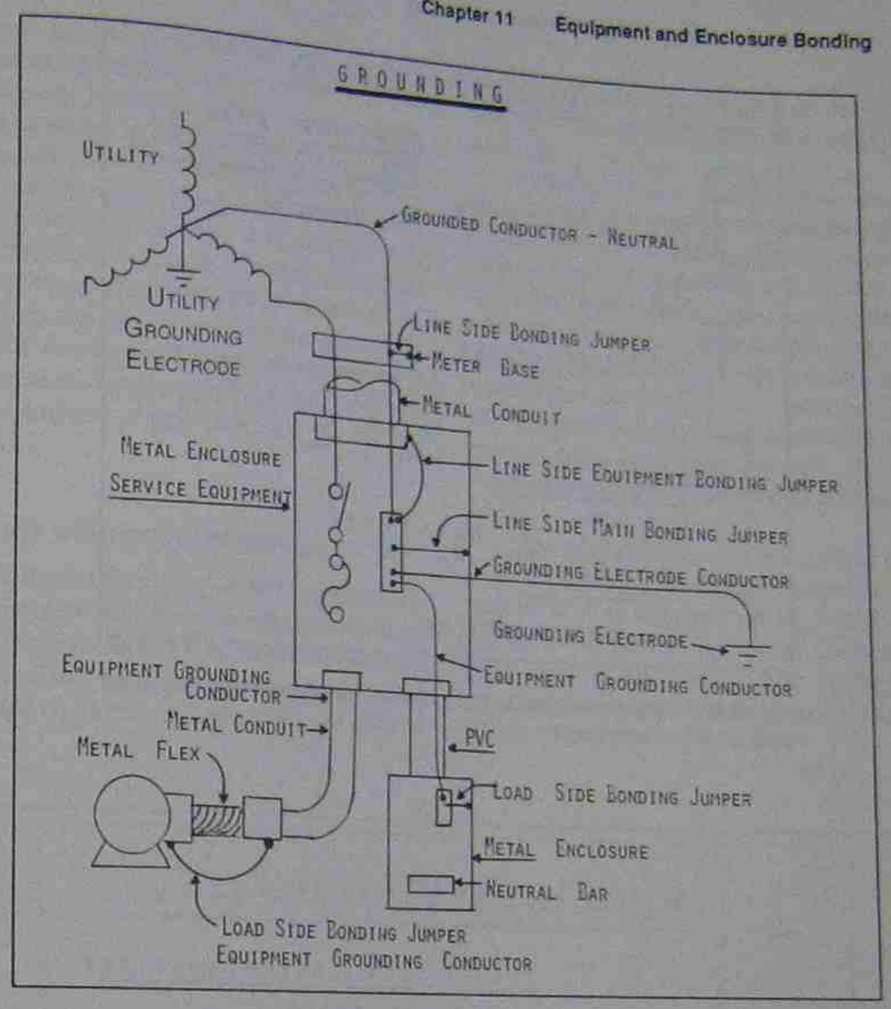


Fig. 11–4 Identification of equipment bonding jumpers on the line and load sides of service equipment.

1. Rigid metal conduit (RMC)
2. Intermediate metal conduit (IMC)
3. Electrical metallic tubing (EMT)
4. Wireways
5. Busways
6. Auxiliary gutters
7. Cable bus
8. Flexible metal conduit not over 6 feet (and other limitations)

Certain cable assemblies with metal outer coverings are permitted by *Section 230-43* for use as service-entrance conductors. The metal covering must have continuity maintained with equipment bonding jumpers. Included are:

1. Type MC cable
2. Mineral-insulated, metal-sheathed cable

Figure 11–6 illustrates the bonding together of all service equipment enclosures, as required by *Section 250-71(a)*. These enclosures will include, but are not limited to, such things as the meter base; pull, junction, or terminal boxes; current transformer (CT) cans; service disconnecting means; service panel; service switchboard; or any metal enclosure that

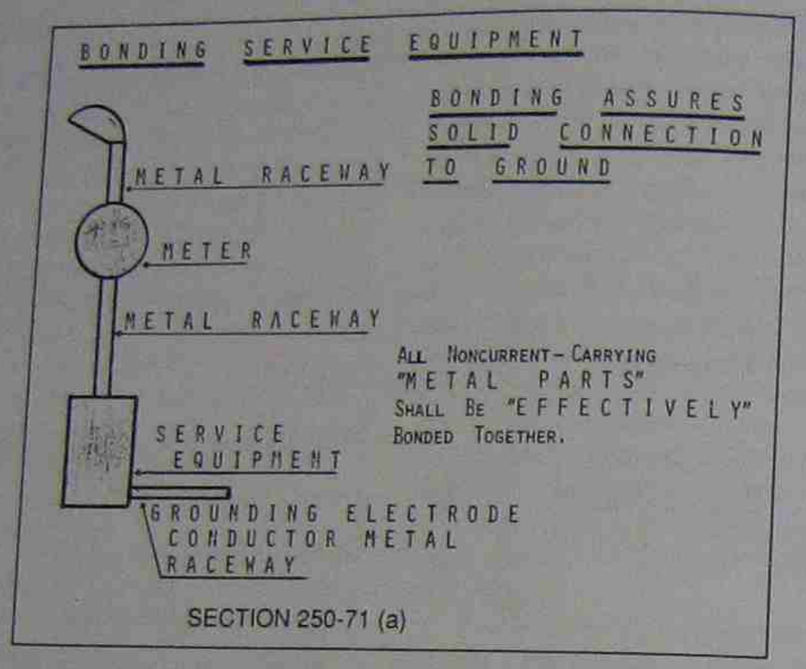


Fig. 11–5 Requirement for bonding together noncurrent-carrying metal parts of service equipment.

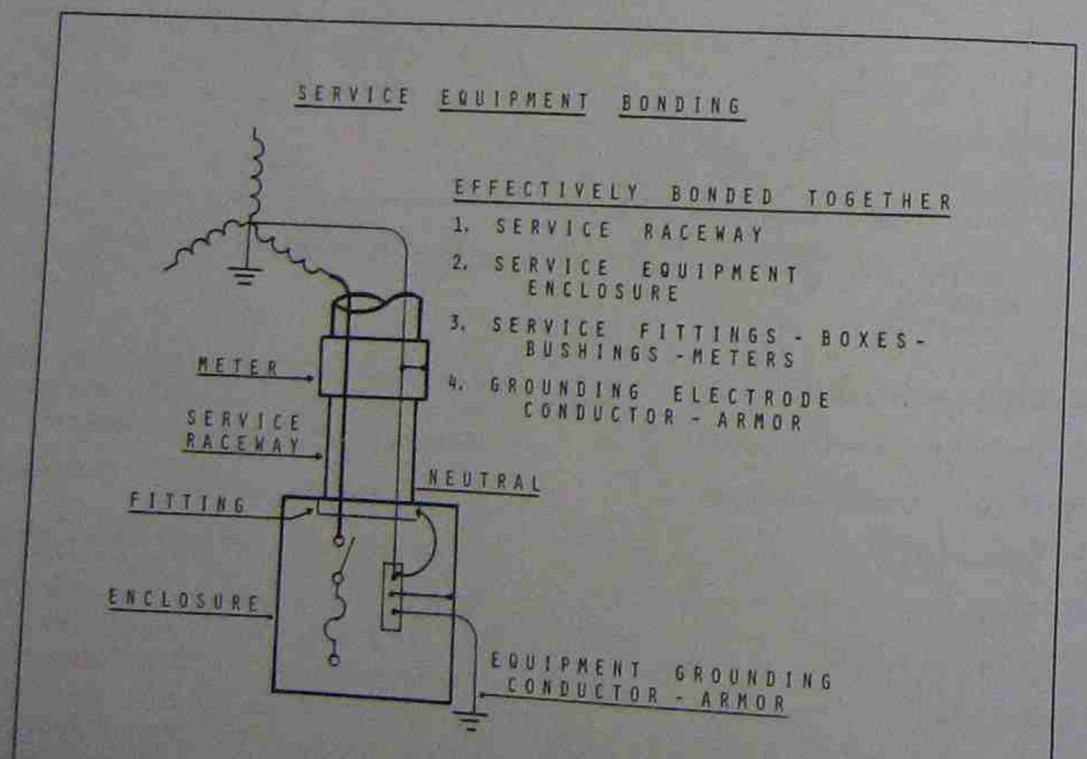


Fig. 11–6 Parts of service equip-

encloses anything ahead of the service disconnecting means.

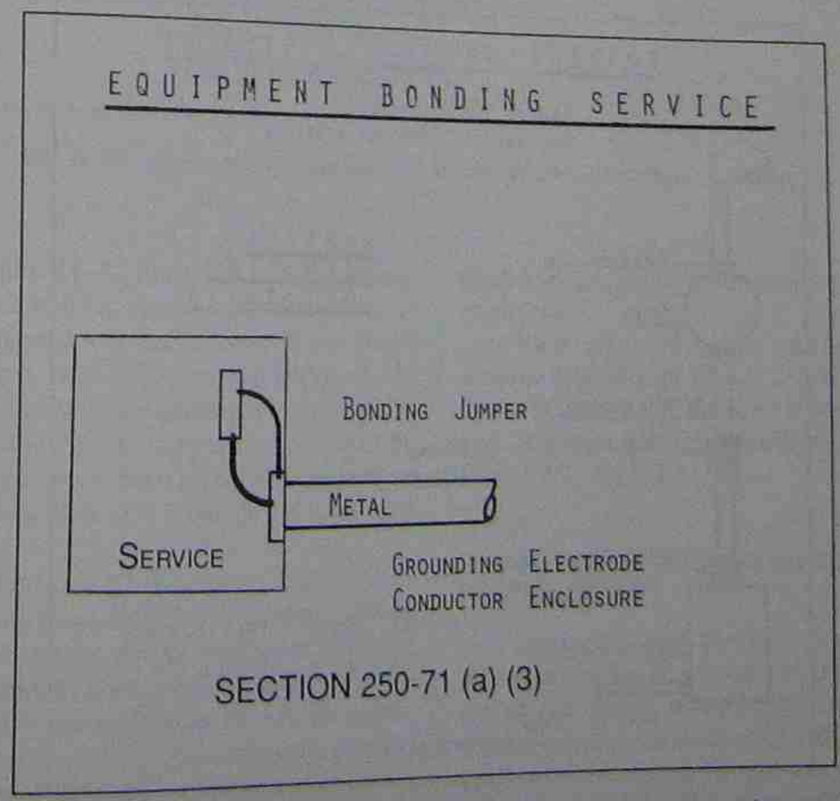
The one bonding requirement often overlooked is stated in *Section 250-71(a)(3)*. This requires the bonding of the metallic raceway or armor enclosing the grounding electrode conductor at the service when it is installed in a metal raceway or armor. *Section 250-92(a)* permits the use of metal raceway, such as metal conduit, to be used to enclose the grounding electrode conductor. The section states that it shall be bonded as illustrated in figure 11–7, and for the same reason as illustrated in chapter 5 of this text.

Methods of Bonding at Service

Methods of bonding, or the things listed for use to make the equipment bonding connections on the supply side of the service, are covered in *Section 250-72*. This section permits the grounded conductor (the neutral) to be used for bonding the service equipment on the LINE SIDE of the service equipment only (figure 11–8).

Threaded fittings and threadless fittings are permitted to be used for bonding the various service enclosures and equipment together; they are illustrated in figure 11–9. *Section 250-72(b)* permits the use of these threaded fittings where rigid metal conduit or intermediate metal conduit is used, but requires them to be madeup wrenchtight. *Section 250-72(c)* permits the use of threadless couplings and connectors when madeup tight, such as those used with rigid metal conduit, intermediate metal conduit, and EMT.

Standard locknuts or bushings shall not be used for bonding the service equipment. This requirement is followed up in *Section 250-72(e)*, which permits the use of the bonding-type locknuts and bonding-type bushings for bonding the service enclosures and equipment (figure 11–10).



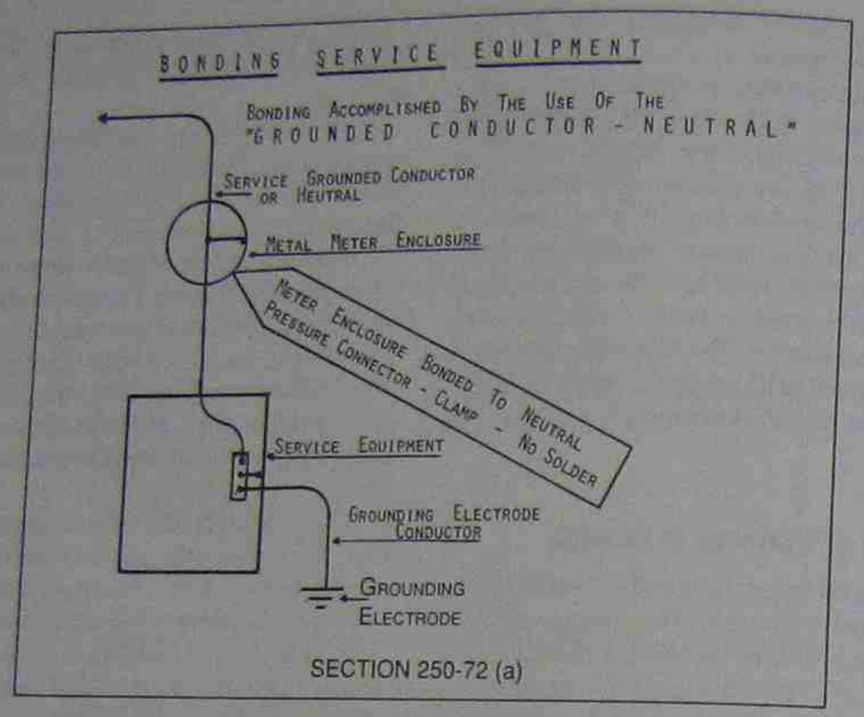


Fig. 11–8 Bonding service equipment using the neutral.

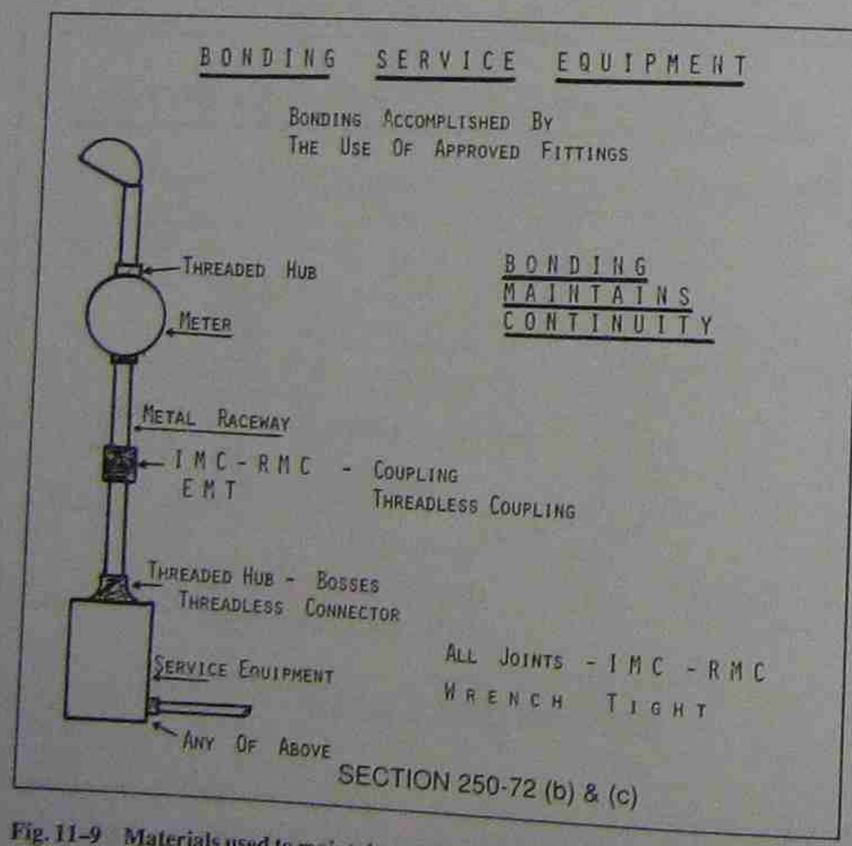


Fig. 11–9 Materials used to maintain continuity when bonding service equipment.

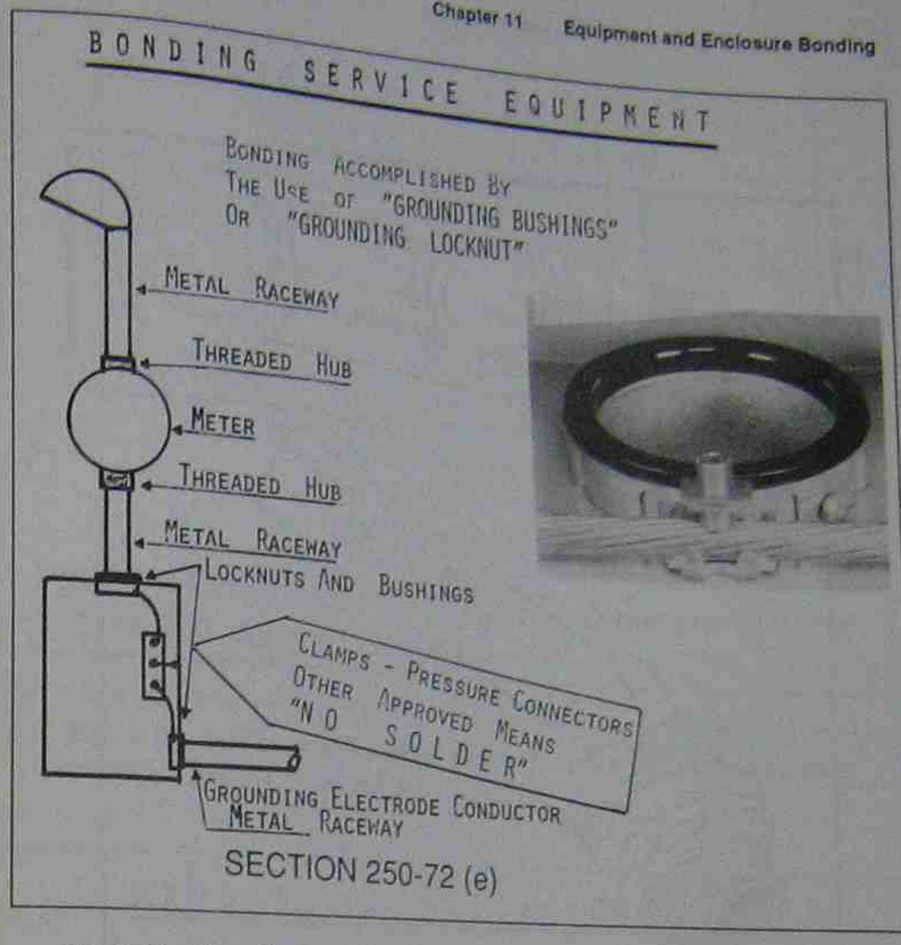


Fig. 11–10 Grounding bushing used with service equipment. Courtesy O.Z./Gedney Co.

Figure 11–11 illustrates a threaded connection or hub for metal conduit that is permitted for maintaining continuity on the line side of the service. The EMT connector, with its shoulder fit with standard locknut, is not permitted for maintaining the continuity on the line side of the service and must have an equipment bonding jumper installed, or a grounding locknut must be used.

Figure 11–12 illustrates *Section 250-72(d)*, which requires a bonding jumper around knockouts in the service equipment when the maximum-size knockout (eccentric or concentric type) is not used. When the smaller knockout is removed, the process often weakens the knockouts left in the equipment; they do not make a good connection and cannot be depended upon to maintain continuity under fault conditions.

When metal-clad cable is used for service-entrance cable (figure 11–13) with a bare conductor in contact with the outer armor or metal tape, it is considered grounded, according to *Section 250-73*.

Sizing Bonding Jumpers on Supply Side of Service

Section 250-79(c) gives three methods for sizing the bonding jumpers on the supply side of the service. When doing so, the size of the service-entrance conductors and the material used for the bonding jumper are taken into consideration. This is the same method that was

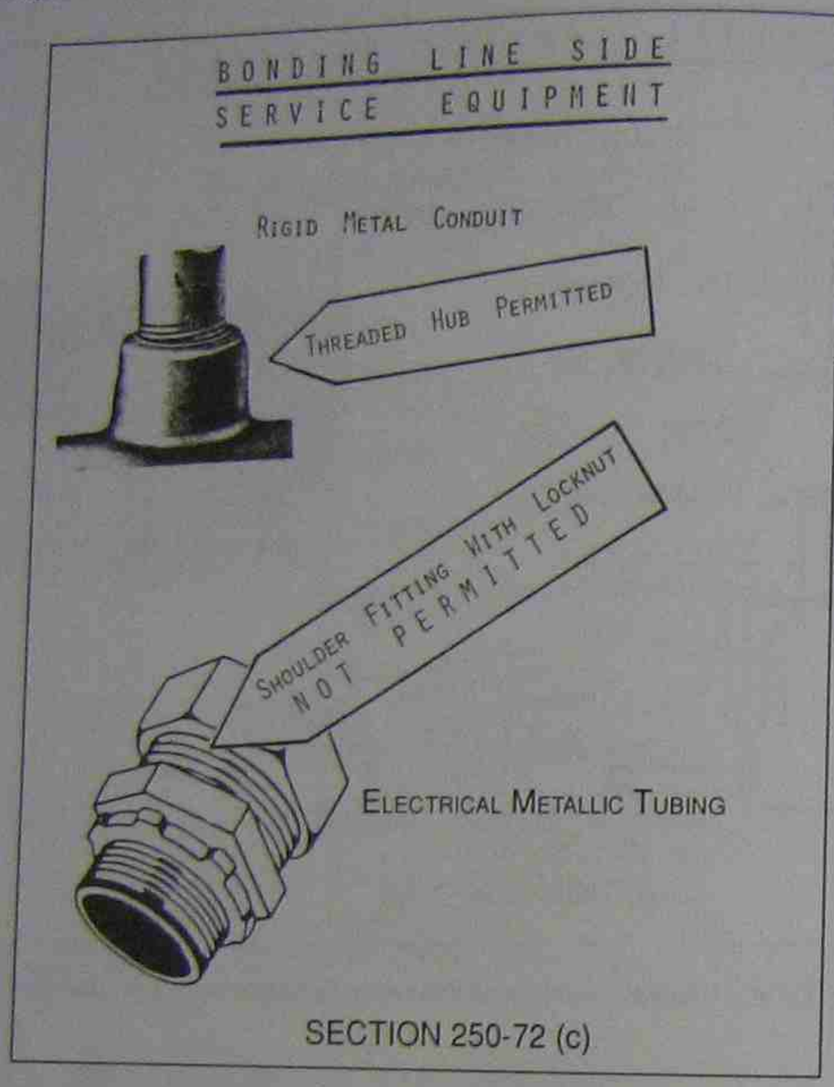


Fig. 11–11 A threaded hub is permitted; an EMT connector with standard locknut is not permitted. Courtesy Appleton Electric Co.

used for calculating the size of the main bonding jumper (chapter 9 of this text).

Method Requirements

1. The bonding jumper shall not be smaller than the size given in *Table 250-94*. This is the same table used for sizing the grounding electrode conductor.
2. This is referred to as the 12-1/2 percent rule. Where the service-entrance phase conductors exceed the sizes listed in *Table 250-94*, which is 1100 MCM for copper and 1700 MCM for aluminum, the bonding jumper shall have an area not less than 12-1/2 percent of the area of the largest phase conductor or conductors, when parallel conductors are used.
3. Where the phase conductors and the bonding jumper are of different materials (copper or aluminum), the minimum size of the bonding jumper shall be based on the assumed use of phase conductors of the same material as the bonding jumper and with an ampacity equivalent to that of the installed phase conductors.

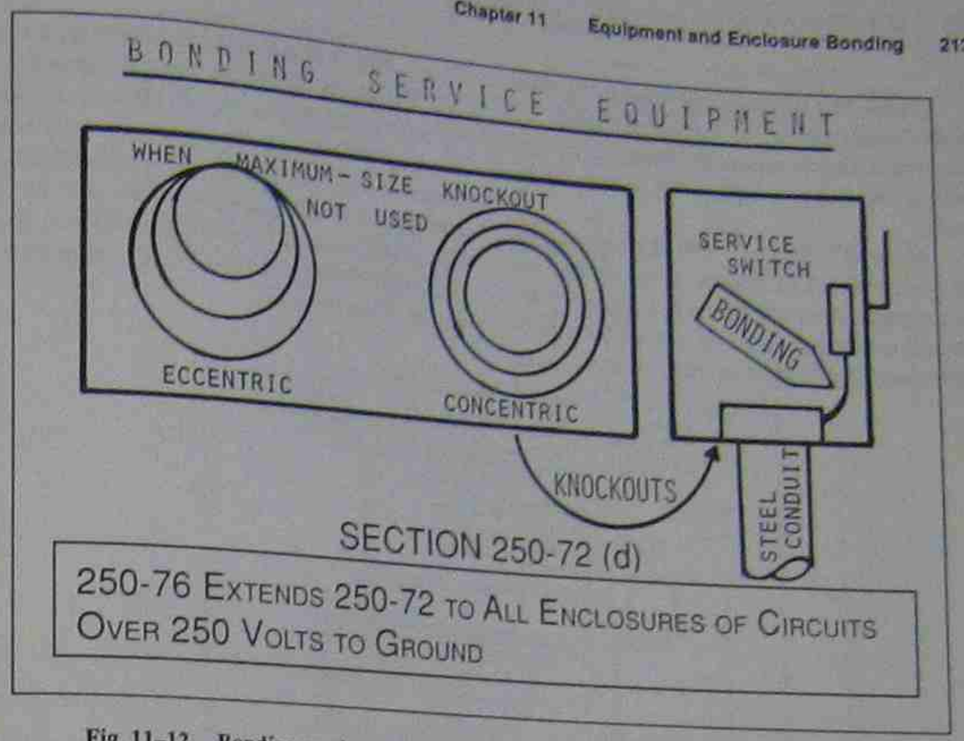


Fig. 11–12 Bonding service equipment when not all eccentric or concentric knockouts are used.

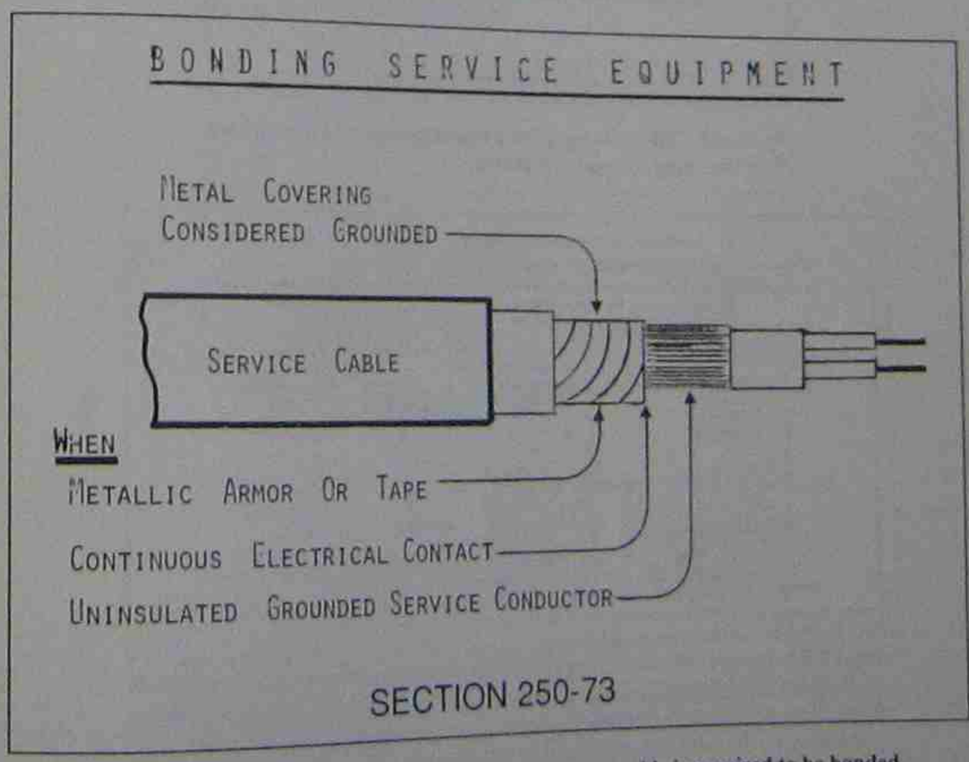


Fig. 11–13 The metal armor or tape of service-entrance cable is required to be bonded.

Table 250-94 is entitled "Grounding Electrode Conductor for AC Systems," but it is also used for sizing the equipment bonding jumpers on the line (supply) side of the service equipment.

Method 1 (figure 11–14) illustrates a service with 500 MCM copper as the service-entrance conductors and the use of a copper equipment bonding jumper. The size of the equipment bonding jumper is read directly from *Table 250-94* (figure 11–15), which requires a No. 1/0 copper equipment bonding jumper.

Method 1 (figure 11–16) illustrates a service with 500 MCM aluminum as service-entrance conductors and the use of an aluminum equipment bonding jumper. The size of the equipment bonding jumper is read directly from *Table 250-94* (figure 11–17) and is required to be No. 1/0 aluminum.

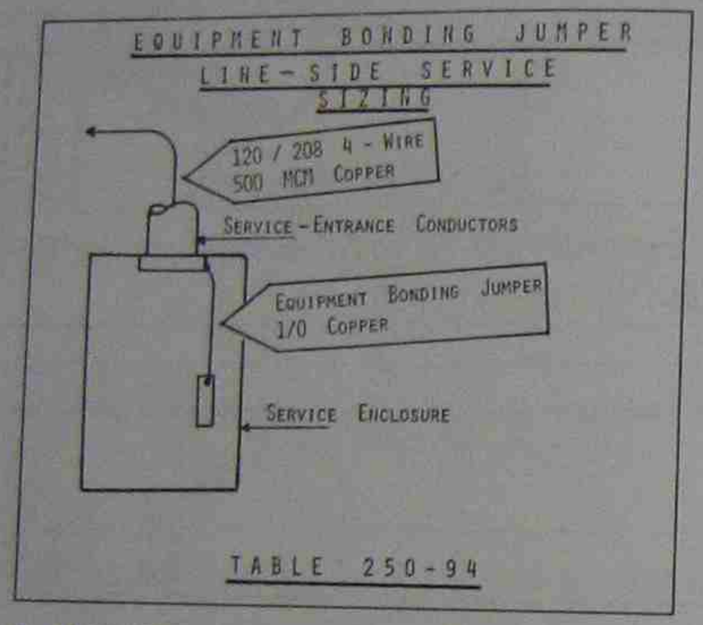


Fig. 11–14 Sizing an equipment bonding jumper on the line side of service using a copper conductor.

Table 250-94
Grounding Electrode Conductor for AC Systems

Size of Largest Service-Entrance Conductor or Equivalent Area for Parallel Conductors		Size of Grounding Electrode Conductor	
Copper	Aluminum or Copper-Clad Aluminum	Copper	*Aluminum or Copper-Clad Aluminum
2 or smaller	0 or smaller	8	6
1 or 0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250 MCM	4	2
Over 3/0 thru 350 MCM	Over 250 MCM thru 500 MCM	2	0
Over 350 MCM thru 600 MCM	Over 500 MCM thru 900 MCM	0	3/0
Over 600 MCM thru 1100 MCM	Over 900 MCM thru 1750 MCM	2/0	4/0
Over 1100 MCM	Over 1750 MCM	3/0	250 MCM

Fig. 11–15 Reading the size of the equipment bonding jumper shown in figure 11–14 from *Table 250-94*. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright ©, 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

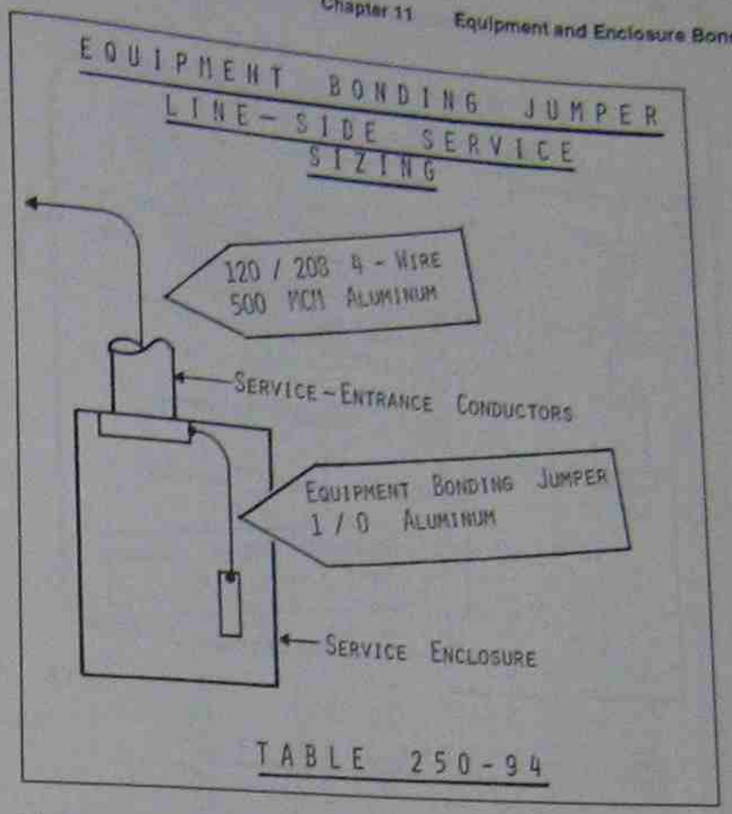


Fig. 11–16 Sizing the equipment bonding jumper on the line side of service when an aluminum conductor is used.

Table 250-94
Grounding Electrode Conductor for AC Systems

Size of Largest Service-Entrance Conductor or Equivalent Area for Parallel Conductors		Size of Grounding Electrode Conductor	
Copper	Aluminum or Copper-Clad Aluminum	Copper	*Aluminum or Copper-Clad Aluminum
2 or smaller	0 or smaller	8	6
1 or 0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250 MCM	4	2
Over 3/0 thru 350 MCM	Over 250 MCM thru 500 MCM	2	0
Over 350 MCM thru 600 MCM	Over 500 MCM thru 900 MCM	0	3/0
Over 600 MCM thru 1100 MCM	Over 900 MCM thru 1750 MCM	2/0	4/0
Over 1100 MCM	Over 1750 MCM	3/0	250 MCM

Fig. 11–17 Reading the size of the equipment bonding jumper shown in figure 11–16 from *Table 250-94*. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright ©, 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

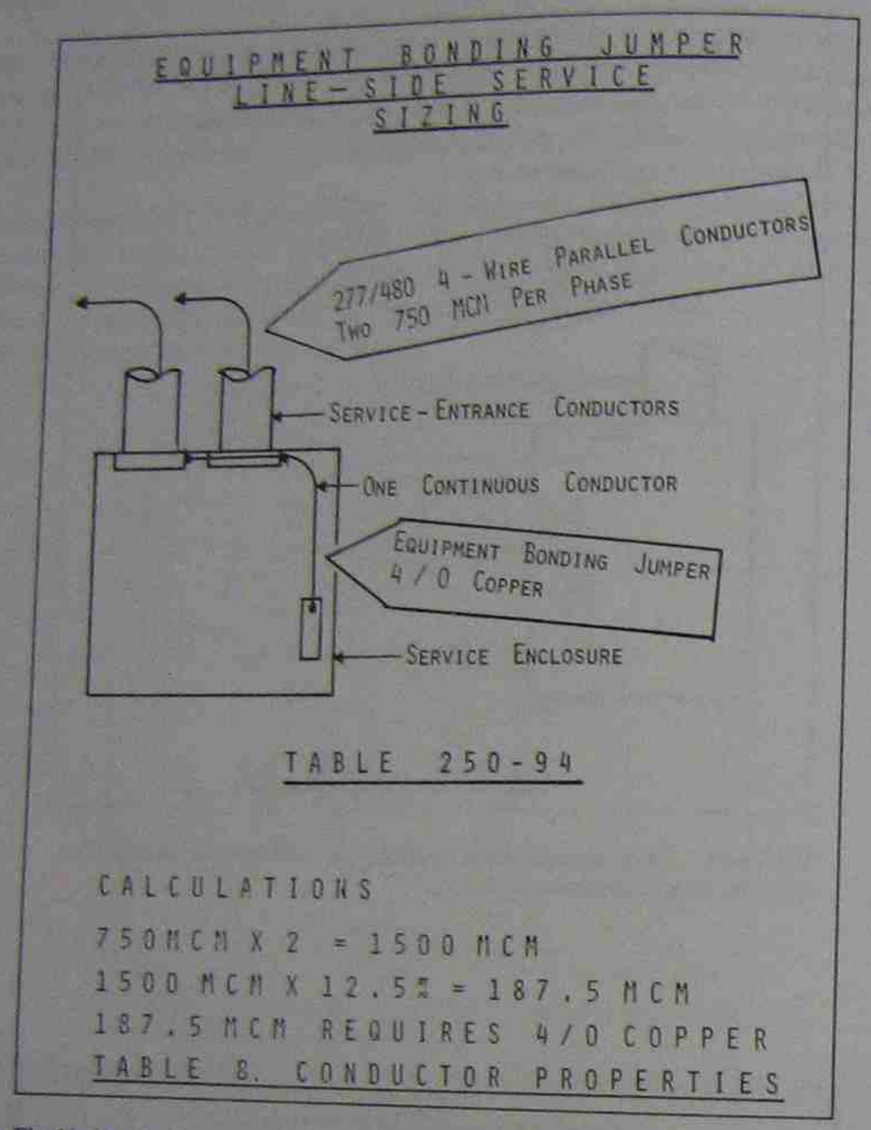


Fig. 11–18 Applying the 12 1/2 percent rule to size the equipment bonding jumper when using copper.

Method 2 (figure 11–18) illustrates a service with 750 MCM copper, two conductors per phase, and the use of a copper equipment bonding jumper. The total cross-sectional area per phase of the service-entrance conductors is

$$2 \times 750 = 1500 \text{ MCM}$$

which is greater than the 1100 MCM copper listed in *Table 250-94*. Therefore, 12 1/2 percent of the total cross-sectional area of a phase conductor shall be used.

$1{,}500{,}000 \times 12\ 1/2\% = 187{,}500$ circular mils

Table 8, Chapter 9 of the Code (figure 11–19) is used to establish a wire size for the equipment bonding jumper. This table shows that 187,500 is larger than No. 3/0 and smaller than No. 4/0; therefore, the larger size will be used and No. 4/0 will be the minimum size of the equipment bonding jumper. One continuous conductor, No. 4/0 copper, is used to bond the two raceways.

CAUTION: The equipment bonding jumper is not broken. It is one continuous wire when used to bond two or more raceways containing parallel service-entrance conductors.

187,500 CM

NEXT SIZE LARGER

Table 8. Conductor Properties

Size AWG/MCM	Area Cir. Mils	Conductors: Stranding Quantity	Stranding Diam. in.	Overall Diam. in.	Overall Area in.²	DC Resistance at 75°C (167°F): Copper Uncoated ohm/MFT	Copper Coated ohm/MFT	Aluminum ohm/MFT
18	1620	1	—	0.040	0.001	7.77	8.08	12.8
18	1620	7	0.015	0.046	0.002	7.95	8.45	13.1
16	2580	1	—	0.051	0.002	4.89	5.08	8.05
16	2580	7	0.019	0.058	0.003	4.99	5.29	8.21
14	4110	1	—	0.064	0.003	3.07	3.19	5.06
14	4110	7	0.024	0.073	0.004	3.14	3.26	5.17
12	6530	1	—	0.081	0.005	1.93	2.01	3.18
12	6530	7	0.030	0.092	0.006	1.98	2.05	3.25
10	10380	1	—	0.102	0.008	1.21	1.26	2.00
10	10380	7	0.038	0.116	0.011	1.24	1.29	2.04
8	16510	1	—	0.128	0.013	0.764	0.786	1.26
8	16510	7	0.049	0.146	0.017	0.778	0.809	1.28
6	26240	7	0.061	0.184	0.027	0.491	0.510	0.808
4	41740	7	0.077	0.232	0.042	0.308	0.321	0.508
3	52620	7	0.087	0.260	0.053	0.245	0.254	0.403
2	66360	7	0.097	0.292	0.067	0.194	0.201	0.319
1	83690	19	0.066	0.332	0.087	0.154	0.160	0.253
1/0	105600	19	0.074	0.373	0.109	0.122	0.127	0.201
2/0	133100	19	0.084	0.419	0.138	0.0967	0.101	0.159
3/0	167800	19	0.094	0.470	0.173	0.0766	0.0797	0.126
4/0	211600	19	0.106	0.528	0.219	0.0608	0.0626	0.100
250	—	37	0.082	0.575	0.260	0.0515	0.0535	0.0847
300	—	37	0.090	0.630	0.312	0.0429	0.0446	0.0707
350	—	37	0.097	0.681	0.364	0.0367	0.0382	0.0605
400	—	37	0.104	0.728	0.416	0.0321	0.0331	0.0529
500	—	37	0.116	0.813	0.519	0.0258	0.0265	0.0424
600		61	0.992	0.893	0.626	0.0214	0.0223	0.0353
700		61	0.107	0.964	0.730	0.0184	0.0189	0.0303
750		61	0.111	0.998	0.782	0.0171	0.0176	0.0282
800		61	0.114	1.03	0.834	0.0161	0.0166	0.0265
900		61	0.122	1.09	0.940	0.0143	0.0147	0.0235
1000		61	0.128	1.15	1.04	0.0129	0.0132	0.0213
1250		91	0.117	1.29	1.30	0.0103	0.0106	0.0169
1500	—	91	0.128	1.41	1.57	0.00858	0.00883	0.0141
1750	—	127	0.117	1.52	1.83	0.00735	0.00756	0.0121
2000	—	127	0.126	1.63	2.09	0.00643	0.00662	0.0106

Fig. 11–19 Using *Table 8* to convert to the next standard wire size. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright ©, 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

Figure 11–20 illustrates service-entrance conductors in metal conduit. After passing through a CT box, they are in PVC, nonmetallic conduit. *Section 250-79(c)* requires that a separate equipment bonding jumper be run in each conduit and sized according to the service-entrance conductors in each conduit. For 750 MCM copper (figure 11–21), *Table 250-94* requires No. 2/0 copper. *Section 310-4* permits the paralleling of No. 2/0 conductors.

Should the service-entrance conductors be 350 MCM copper, as in figure 11–22, *Table 250-94* requires a No. 2 copper equipment bonding jumper in each conduit. *Section 310-4* limits parallel conductors to No. 1/0 and larger, and the No. 2 copper equipment bonding jumper calculated here is smaller than No. 1/0. *Section 310-4* makes an exception when sizing the equipment grounding conductor according to *Table 250-95* but not when using *Table 250-94*, which is used to size this equipment bonding jumper. Therefore, the smallest parallel equipment grounding conductor that is permitted is the minimum size for parallel conductors—No. 1/0.

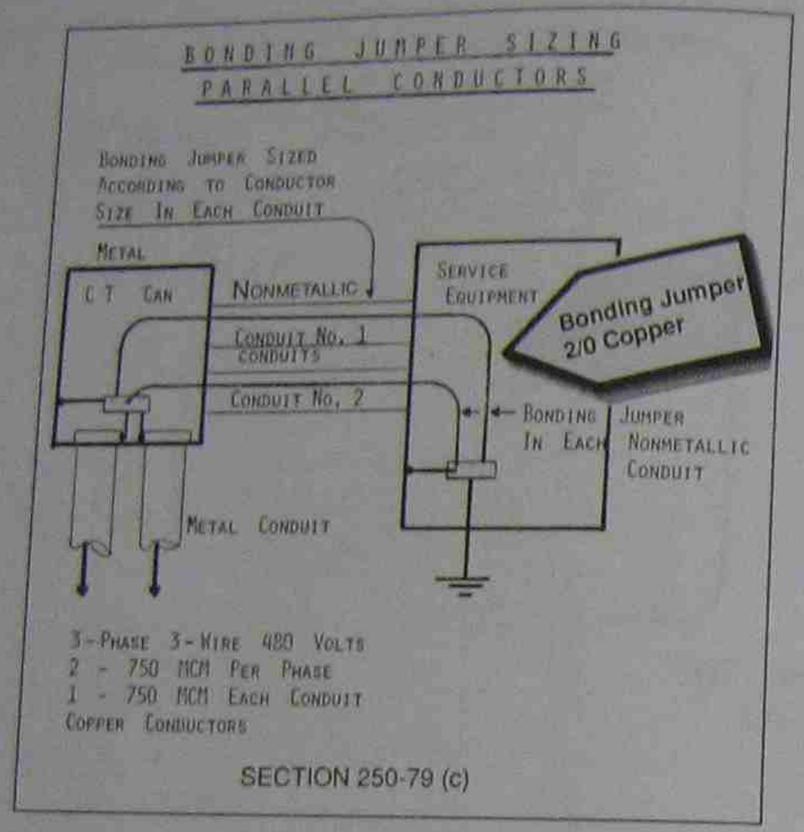


Fig. 11–20 Sizing the equipment bonding jumpers installed with 750 MCM copper service-entrance conductors in parallel, nonmetallic raceways.

Table 250-94
Grounding Electrode Conductor for AC Systems

Size of Largest Service-Entrance Conductor or Equivalent Area for Parallel Conductors		Size of Grounding Electrode Conductor	
Copper	Aluminum or Copper-Clad Aluminum	Copper	*Aluminum or Copper-Clad Aluminum
2 or smaller	0 or smaller	8	6
1 or 0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250 MCM	4	2
Over 3/0 thru 350 MCM	Over 250 MCM thru 500 MCM	2	0
Over 350 MCM thru 600 MCM	Over 500 MCM thru 900 MCM	0	3/0
Over 600 MCM thru 1100 MCM	Over 900 MCM thru 1750 MCM	2/0	4/0
Over 1100 MCM	Over 1750 MCM	3/0	250 MCM

Fig. 11–21 Reading the size of the copper equipment bonding jumpers shown in figure 11–20 from *Table 250-94*. One No. 2/0 is required in each raceway.
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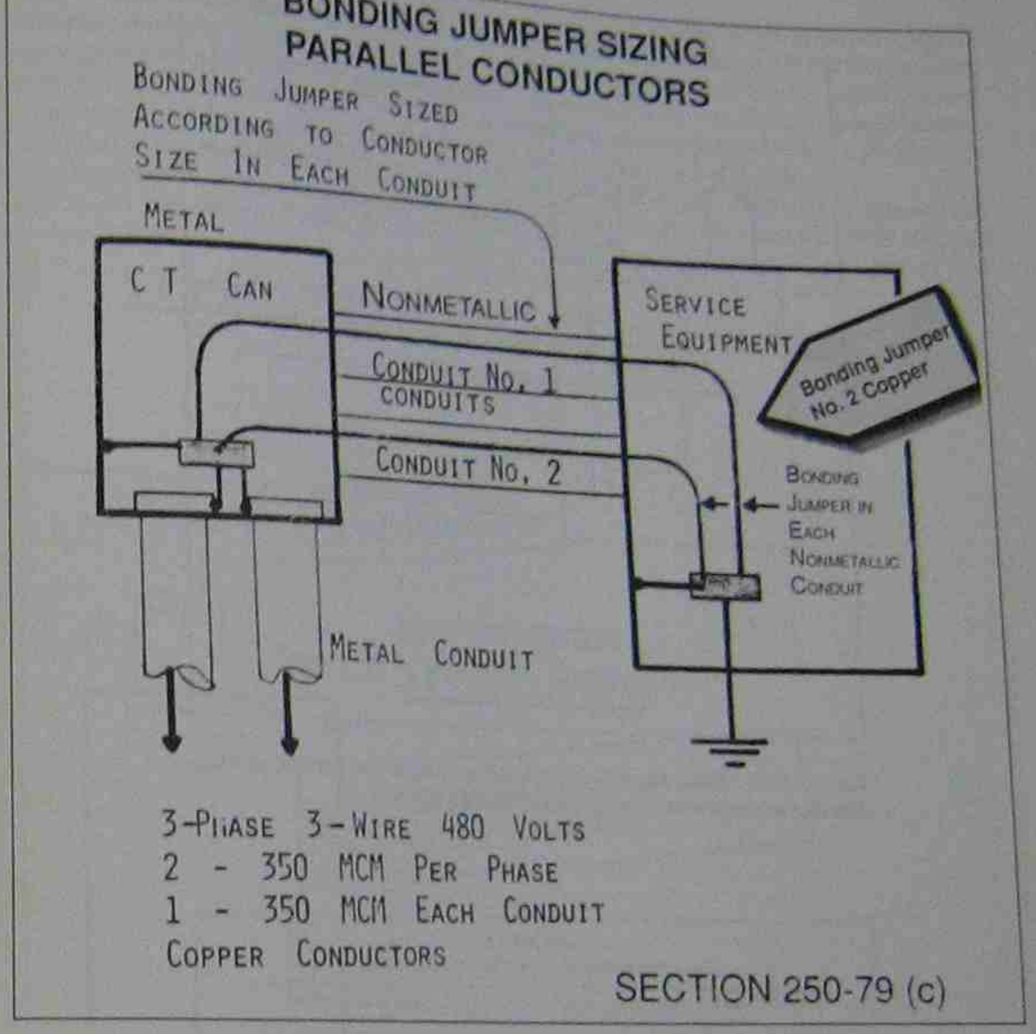

Fig. 11–22 Sizing the equipment bonding jumpers installed with 350 MCM copper service-entrance conductors in parallel, nonmetallic raceways.

Comment: It is anticipated that this will be changed in the next Code revision and an equipment bonding jumper smaller than No. 1/0 will be permitted. Therefore, the smaller conductor may now be permitted in various localities.

Another installation of the equipment bonding jumper with parallel conductors, when more than one metal raceway is used for service-entrance conductors, is illustrated in figure 11–23. An individual equipment bonding jumper is run to each metal raceway and is sized according to the size of the service-entrance conductors in the raceway. Each metal conduit contains 500 MCM copper conductors; therefore, the size of each of the equipment bonding jumpers is based on the 500 MCM conductors in each conduit and is read directly from *Table 250-94*—No. 1/0 copper (figure 11–24).

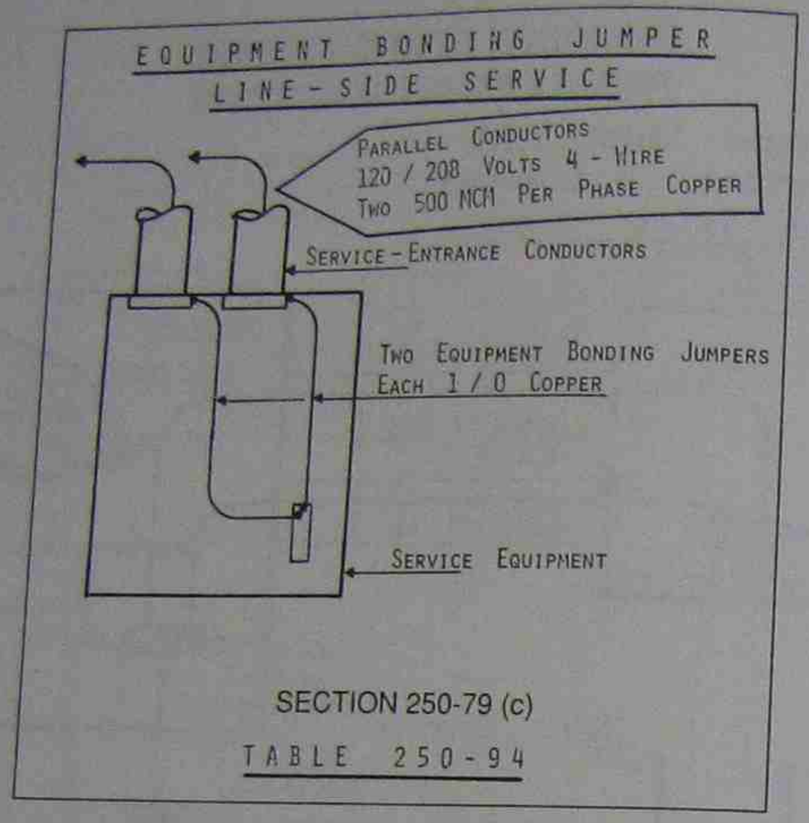

Fig. 11–23 Sizing the equipment bonding jumper for parallel service-entrance conduits using two equipment bonding jumpers.

Table 250-94
Grounding Electrode Conductor for AC Systems

Size of Largest Service-Entrance Conductor or Equivalent Area for Parallel Conductors		Size of Grounding Electrode Conductor	
Copper	Aluminum or Copper-Clad Aluminum	Copper	*Aluminum or Copper-Clad Aluminum
2 or smaller	0 or smaller	8	6
1 or 0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250 MCM	4	2
Over 3/0 thru 350 MCM	Over 250 MCM thru 500 MCM	2	0
Over 350 MCM thru 600 MCM	Over 500 MCM thru 900 MCM	0	3/0
Over 600 MCM thru 1100 MCM	Over 900 MCM thru 1750 MCM	2/0	4/0
Over 1100 MCM	Over 1750 MCM	1/0	250 MCM

Fig. 11–24 **Reading the size of the copper equipment bonding jumpers shown in figure 11–23. One No. 1/0 is required in each metal raceway.** Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright ©, 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

Method 3 (figure 11–25) illustrates the use of 500 MCM THHN aluminum as the service-entrance conductors and the use of a copper equipment bonding jumper. For calculating the size of the equipment bonding jumper, the aluminum service-entrance conductors are assumed to be replaced with copper conductors of equal ampacity. This is accomplished in figure 11–26 with the use of *Table 310-16*, which indicates it will take 350 MCM THHN copper to equal the ampacity of the 500 MCM aluminum. The next step is to use the 350 MCM assumed copper to read the size of the equipment bonding jumper directly from *Table 250-94* (figure 11–27). It is No. 2 copper.

Figure 11–28 illustrates a three-phase, 480-volt ungrounded service with one 750 MCM copper conductor per phase. An

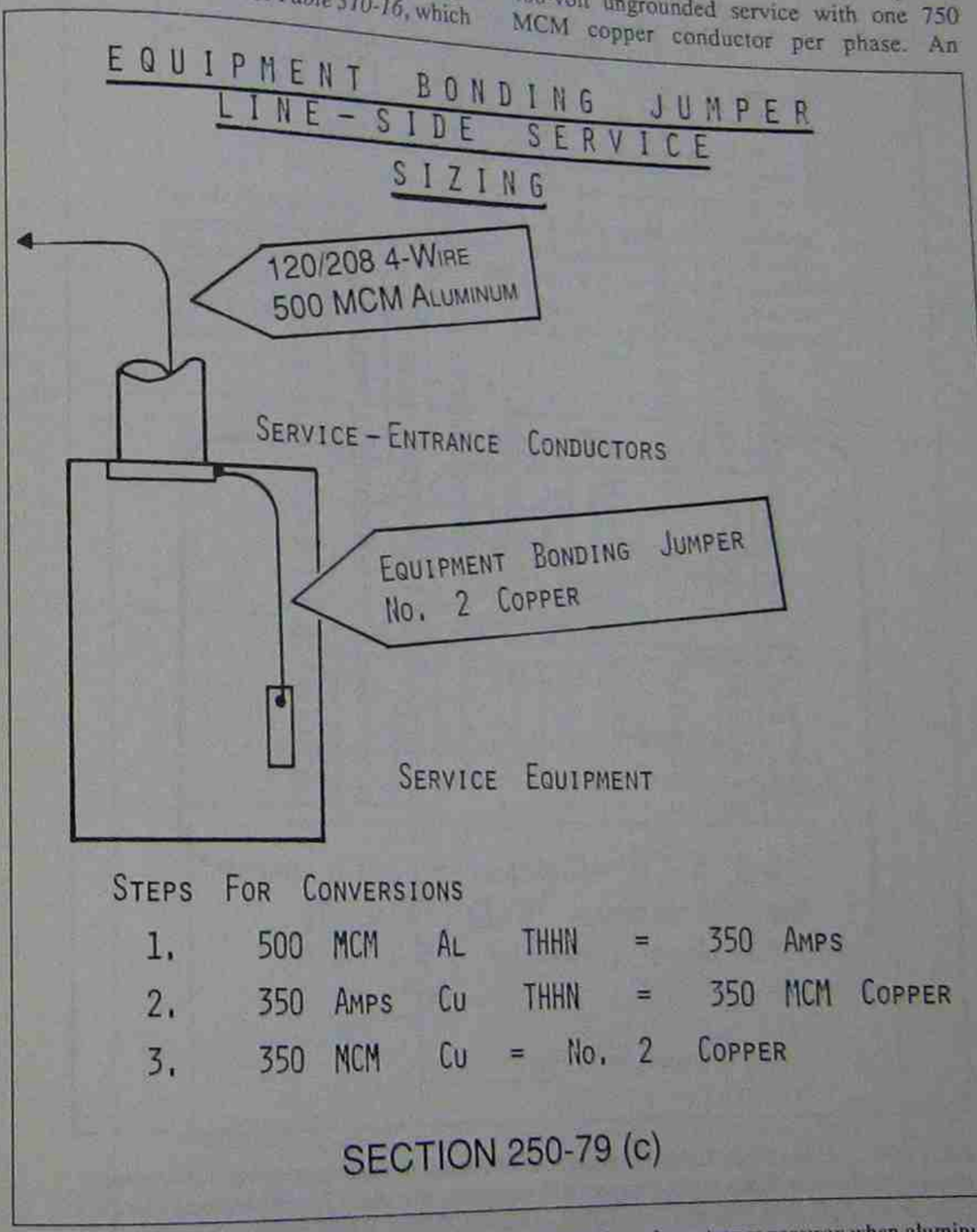

Fig. 11–25 Sizing the equipment bonding jumper for metal service-entrance raceway when aluminum service-entrance conductors are installed and a copper equipment bonding jumper is installed.

Table 310-16. Ampacities of Not More than Three Single Insulated Conductors, Rated 0 through 2000 Volts, in Raceway in Free Air and Ampacities of Cable Types AC, NM, NMC and SE

Based on Ambient Air Temperature of 30°C (86°F).

Size	Temperature Rating of Conductor. See Table 310-13.								Size
	60°C (140°F)	75°C (167°F)	85°C (185°F)	90°C (194°F)	60°C (140°F)	75°C (167°F)	85°C (185°F)	90°C (194°F)	
AWG MCM	TYPES TW, UF	TYPES RHW, THHW, THW, THWN, XHHW, USE, ZW	TYPE V	TYPES TA, TBS, SA, AVB, SIS, FEP, FEPB, MI, RHH, THHN, XHHW	TYPES TW, UF	TYPES RHW, THHW, THW, THWN, XHHW, USE	TYPE V	TYPES TA, TBS, SA, AVB, SIS, RHH, THHN, XHHW	AWG MCM
	COPPER				ALUMINUM OR COPPER-CLAD ALUMINUM				
18				14					
16			18	18					
14	20†	20†	25	25†					
12	25†	25†	30	30†	20†	20†	25	25†	12
10	30	35†	40	40†	25	30†	30	35†	10
8	40	50	55	55	30	40	40	45	8
6	55	65	70	75	40	50	55	60	6
4	70	85	95	95	55	65	75	75	4
3	85	100	110	110	65	75	85	85	3
2	95	115	125	130	75	90	100	100	2
1	110	130	145	150	85	100	110	115	1
1/0	125	150	165	170	100	120	130	135	1/0
2/0	145	175	190	195	115	135	145	150	2/0
3/0	165	200	215	225	130	155	170	175	3/0
4/0	195	230	250	260	150	180	195	205	4/0
250	215	255	275	290	170	205	220	230	250
300	240	285	310	320	190	230	250	255	300
350	260	310	340	350	210	250	270	280	350
400	280	335	365	380	225	270	295	305	400
500	320	380	415	430	260	310	335	350	500
600	355	420	460	475	285	340	370	385	600
700	385	460	500	520	310	375	405	420	700
750	400	475	515	535	320	385	420	435	750
800	410	490	535	555	330	395	430	450	800
900	435	520	565	585	355	425	465	480	900
1000	455	545	590	615	375	445	485	500	1000
1250	495	590	640	665	405	485	535	545	1250
1500	520	625	680	705	435	520	565	585	1500
1750	545	650	705	735	455	545	595	615	1750
2000	560	665	725	750	470	560	610	630	2000

AMPACITY CORRECTION FACTORS

Ambient Temp. °C	For ambient temperatures other than 30°C (86°F), multiply the ampacities shown above by the appropriate factor shown below.								Ambient Temp. °F
21-25	1.08	1.05	1.04	1.04	1.08	1.05	1.04	1.04	70-77
26-30	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	79-86
31-35	91	94	95	96	91	94	95	96	88-95
36-40	82	88	90	91	82	88	90	91	97-104
41-45	71	82	85	87	71	82	85	87	106-113
46-50	58	75	80	82	58	75	80	82	115-122
51-55	41	67	74	76	41	67	74	76	124-131
56-60		58	67	71		58	67	71	133-140
61-70		33	52	58		33	52	58	142-158
71-80			30	41			30	41	160-176

500 MCM ALUMINUM = 350 AMPS
AND IS ASSUMED TO BE EQUAL TO
350 AMPS COPPER = 350 MCM

Fig. 11–26 **Using *Table 310-16* for conversion of aluminum conductors to equivalent copper conductors shown in figure 11–24.** Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright ©, 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

Table 250-94
Grounding Electrode Conductor for AC Systems

Size of Largest Service-Entrance Conductor or Equivalent Area for Parallel Conductors		Size of Grounding Electrode Conductor	
Copper	Aluminum or Copper-Clad Aluminum	Copper	*Aluminum or Copper-Clad Aluminum
2 or smaller	0 or smaller	8	6
1 or 0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250 MCM	4	2
Over 3/0 thru 350 MCM	Over 250 MCM thru 500 MCM	2	0
Over 350 MCM thru 600 MCM	Over 500 MCM thru 900 MCM	0	3/0
Over 600 MCM thru 1100 MCM	Over 900 MCM thru 1750 MCM	2/0	4/0
Over 1100 MCM	Over 1750 MCM	3/0	250 MCM

Fig. 11–27 **Reading *Table 250-94* for the size of the copper equipment bonding jumper shown in figure 11–25.** Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright ©, 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

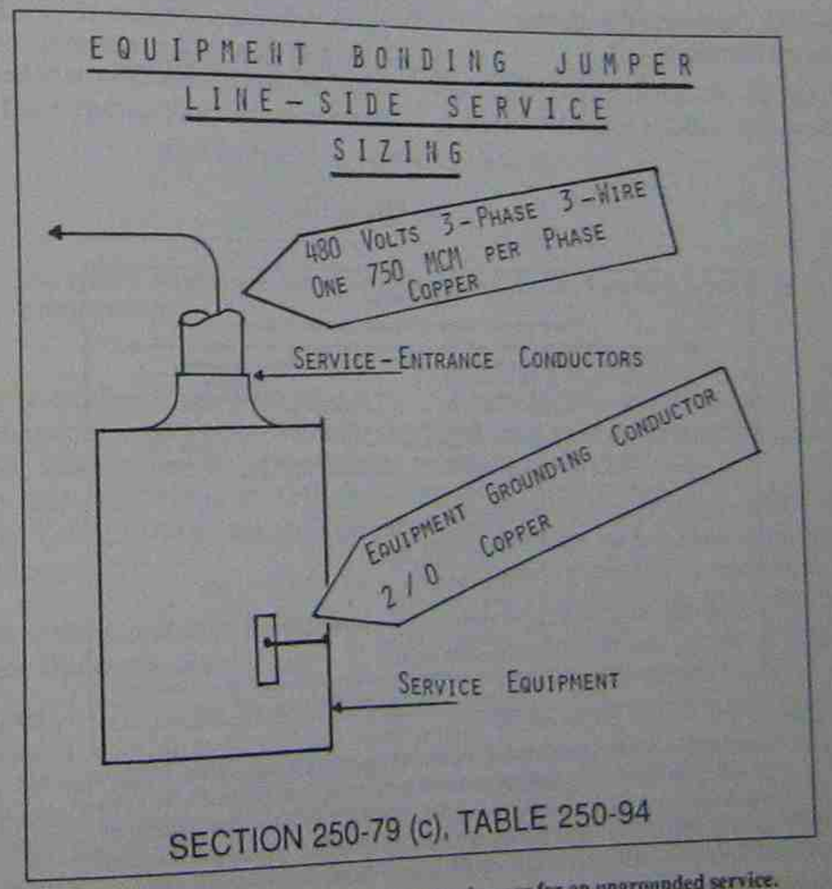

Fig. 11–28 **Sizing the equipment bonding jumper for an ungrounded service.**

equipment bonding jumper is required for ungrounded systems, the same as for grounded systems. An equipment bonding jumper is installed. The size of the equipment bonding jumper is calculated the same as any other equipment bonding jumper on the line side of the service equipment. Therefore, the size of the equipment bonding jumper in this illustration is based on the size of the service-entrance conductor and is read directly from *Table 250-94* (figure 11–29). It is required to be No. 2/0 copper.

It looks like a main bonding jumper has been installed in figure 11–28. A point to remember about the main bonding jumper is that it is only used with a grounded system. This is an ungrounded installation. Therefore, it is an equipment bonding jumper on the line side of the service.

Grounding Electrode Conductor Enclosure Bonding

Figure 11–30 illustrates a grounding electrode conductor installed with EMT, which is used to protect part of the length of the grounding electrode conductor. The EMT is connected to the service enclosure with a shoulder-type connector with a standard locknut, which is not acceptable for maintaining continuity at the service equipment according to *Section 250-71(a)*. Therefore, the metal raceway shall be bonded at the service with an equipment bonding jumper. The equipment bonding jumper is sized the same as the grounding electrode conductor. The No. 3/0 copper service-entrance conductor requires a No. 2 copper grounding electrode conductor and the size of the equipment bonding jumper is read directly from *Table 250-94*.

Figure 11–30 shows that where the metal raceway ends, the raceway must be bonded to the grounding electrode conductor according to *Section 250-92(b)*. The Code does not specify in *Section 250-92(b)* or *Section 250-71(a)(3)* where this bonding is required, or just how the size of the bonding jumper shall be calculated. It is part of the grounding electrode conductor. Therefore, there is no need for it to be larger than the grounding electrode conductor and it could possibly be smaller. A safe assumption is to make it the same size as the grounding electrode conductor, based on the size of the service-entrance conductors. Figure 11–31 illustrates the use of *Table 250-94* for the No. 2 copper bonding jumper.

Table 250-94
Grounding Electrode Conductor for AC Systems

Size of Largest Service-Entrance Conductor or Equivalent Area for Parallel Conductors		Size of Grounding Electrode Conductor	
Copper	Aluminum or Copper-Clad Aluminum	Copper	*Aluminum or Copper-Clad Aluminum
2 or smaller	0 or smaller	8	6
1 or 0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250 MCM	4	2
Over 3/0 thru 350 MCM	Over 250 MCM thru 500 MCM	2	0
Over 350 MCM thru 600 MCM	Over 500 MCM thru 900 MCM	0	3/0
Over 600 MCM thru 1100 MCM	Over 900 MCM thru 1750 MCM	2/0	4/0
Over 1100 MCM	Over 1750 MCM	3/0	250 MCM

Fig. 11–29 Reading the size of the equipment bonding jumper shown in figure 11–28 from *Table 250-94*. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright ©, 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

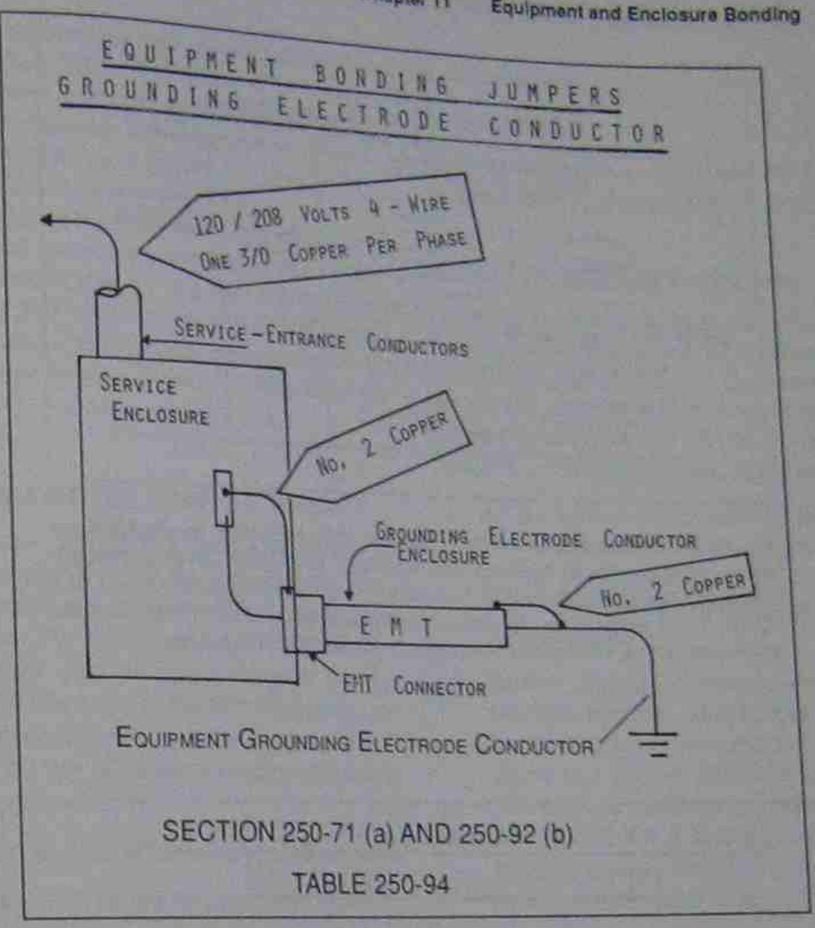

Fig. 11–30 Bonding when the grounding electrode conductor is partially protected by a metal raceway.

Flexible Metal Conduit in Service-Entrance Raceway

Figure 11–32 illustrates the use of flexible metal conduit installed as part of the metal raceway for the service-entrance conductors. This is covered in *Section 230-43* and *Section 250-79*. The flexible metal conduit may be installed between the service-entrance raceway and the service equipment or in any part of the service-entrance raceway. However, there are some restrictions on the use of the flexible metal conduit. These are:

1. Regardless of the length of flexible metal conduit when it is installed as part of the service equipment or raceway, there shall be a bonding jumper installed around it.
2. It cannot be over 6 feet in length when installed between raceways.
3. It cannot be over 6 feet in length when installed between raceway and service equipment.

Comment: The maximum length of the flexible metal conduit allowed is 6 feet. Should a 4-foot length of flexible metal conduit be used,

Table 250-94
Grounding Electrode Conductor for AC Systems

Size of Largest Service-Entrance Conductor or Equivalent Area for Parallel Conductors		Size of Grounding Electrode Conductor	
Copper	Aluminum or Copper-Clad Aluminum	Copper	*Aluminum or Copper-Clad Aluminum
2 or smaller	0 or smaller	8	6
1 or 0	2/0 or 3/0	6	4
2/0 or 3/0	4/0 or 250 MCM	4	2
Over 3/0 thru 350 MCM	Over 250 MCM thru 500 MCM	2	0
Over 350 MCM thru 600 MCM	Over 500 MCM thru 900 MCM	0	3/0
Over 600 MCM thru 1100 MCM	Over 900 MCM thru 1750 MCM	2/0	4/0
Over 1100 MCM	Over 1750 MCM	3/0	250 MCM

Fig. 11–31 Reading *Table 250-94* for the size of the equipment bonding jumper shown in figure 11–30. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright ©, 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

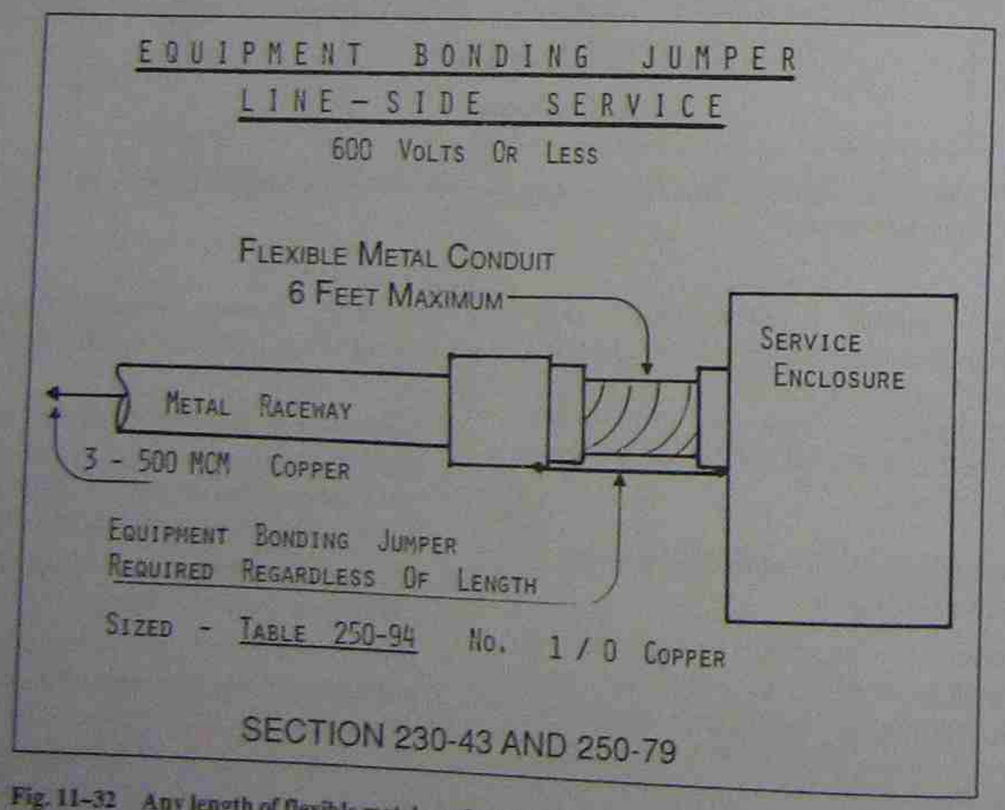

Fig. 11–32 Any length of flexible metal conduit is required to be bonded when it is part of the service-entrance raceway.

an equipment bonding jumper would also have to be installed. When flexible metal conduit is used as any part of the service-entrance conductor's raceway, it shall have an equipment bonding jumper installed with it. It can be installed inside or outside the raceway.

The size of the equipment bonding jumper is calculated according to the size of the service-entrance conductors. In this case the raceway contains a 500 MCM copper conductor; therefore, the size of the equipment bonding jumper is read directly from *Table 250-94* and is required to be No. 1/0 copper.

BONDING OTHER THAN AT SERVICE

Section 250-75 is almost a summary of other sections of the Code. It applies to maintaining continuity of the equipment grounding conductor. The following is an outline of *Section 250-75* and the many things it covers, especially when any of the following items are used as the equipment bonding jumper, with or without the use of a supplementary equipment grounding conductor.

1. They shall be effectively bonded together.
2. They shall assure electrical continuity.
3. They shall have the ampacity to conduct safely any fault current that might be imposed on them.
4. They shall make a good electrical contact by having the contact surface free of any nonconductive paint or similar coatings. Unless the fittings used are so designed, it makes it unnecessary to remove the nonconductive material.

Those items used as an equipment bonding jumper are:

1. Metal raceways
2. Metal cable trays
3. Armored cable
4. Metal-sheathed cable
5. Metal enclosures
6. Metal frames
7. Metal fittings
8. Other noncurrent-carrying parts that serve as equipment grounding conductors

Bonding Prepunched Knockouts

When knockouts are prepunched in a box or equipment enclosure and all the knockouts are not used, there is concern about continuity and the amount of cross-sectional area of the punched metal remaining. The Code addresses these concerns at three points. These are:

1. At the service, as illustrated in figure 11–12, locknuts and bushings are not depended on for continuity; an equipment bonding jumper is required regardless of system voltage.
2. *Section 250-76* addresses prepunched knockout bonding, other than at the service, when all knockouts are not used. When the system is over 250 volts to ground, locknuts and bushings are not to be depended upon for grounding continuity. A bonding jumper is required to assure continuity of the ground path.

Examples of common distribution systems where the voltage exceeds 250 volts to ground and equipment bonding jumpers are required to be installed are:

- Three-phase, four-wire, wye, 277/480 volts
- Three-phase, three-wire, delta, 480 volts

3. This is not listed as such, but for other than at the service for system and circuits of less than 240 volts to ground, locknuts and bushings are permitted for equipment bonding of metal raceway enclosures to the equipment enclosures.

Examples of common distribution systems where the voltage does not exceed 250 volts to ground and locknuts and bushings are permitted for continuity of the equipment grounding conductor are:

- Single phase, 120/240 volts
- Three-phase, four-wire, wye, 120/208 volts
- Three-phase, four-wire, delta, 120/240 volts
- Three-phase, three-wire, delta, 240 volts
- Three-phase, three-wire, wye, 208 volts

Where prepunched knockouts are completely removed (figure 11–33) or there are no prepunched knockouts and knockouts are made

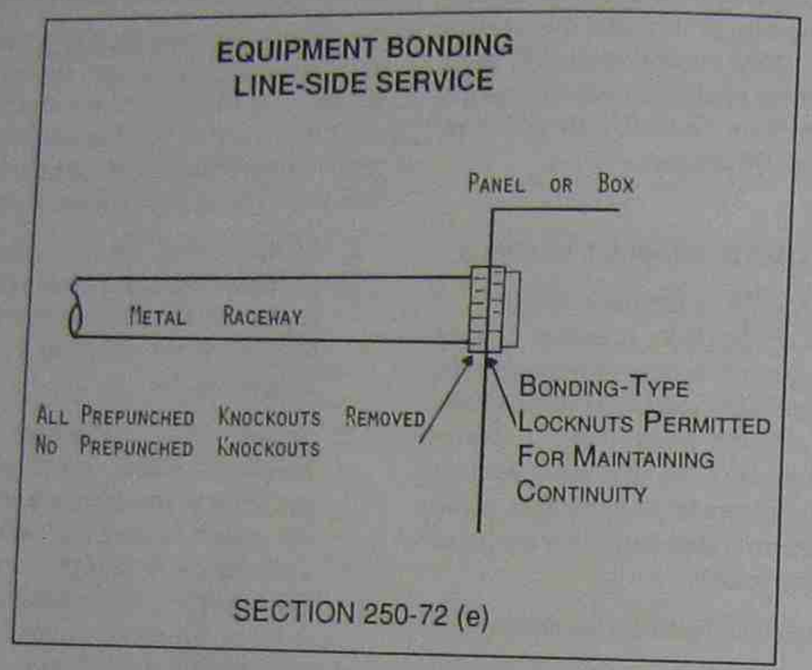

Fig. 11–33 A bonding-type locknut is permitted for line-side service continuity.

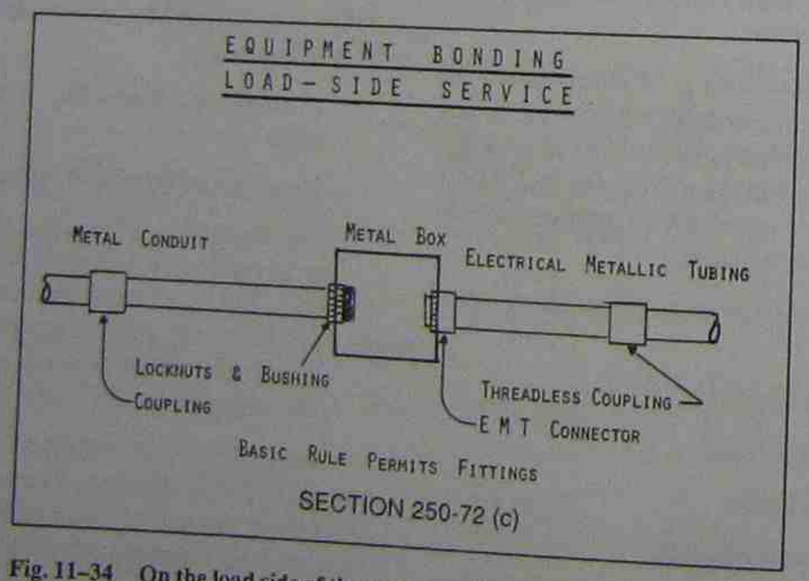

Fig. 11–34 On the load side of the service equipment, the basic rule permits the use of listed fittings for grounding continuity.

by some other means, the voltage is not mentioned and the equipment bonding is permitted by *Section 250-72* to be accomplished by the use of the following:

1. Threadless couplings
2. Cable connectors with metal-sheathed cable
3. Two locknuts—one inside and one outside the enclosure for rigid metal conduit or intermediate metal conduit.
4. Fittings that seat firmly against the enclosure such as electrical metallic tubing connectors and cable connectors; this basic rule illustrated in figure 11–34

Bonding Loose-Fitting Sections

At any point where there is not a firm metal-to-metal contact between the two parts of a metal raceway system, an equipment bonding jumper shall be installed (figure 11–35) as required by *Section 250-77*. The equipment bonding jumper may be installed inside or outside a raceway or an enclosure (figure 11–36). When the equipment bonding jumper is installed outside the enclosure, the equipment bonding jumper shall:

1. not exceed 6 feet,
2. be routed with the raceway or enclosure.

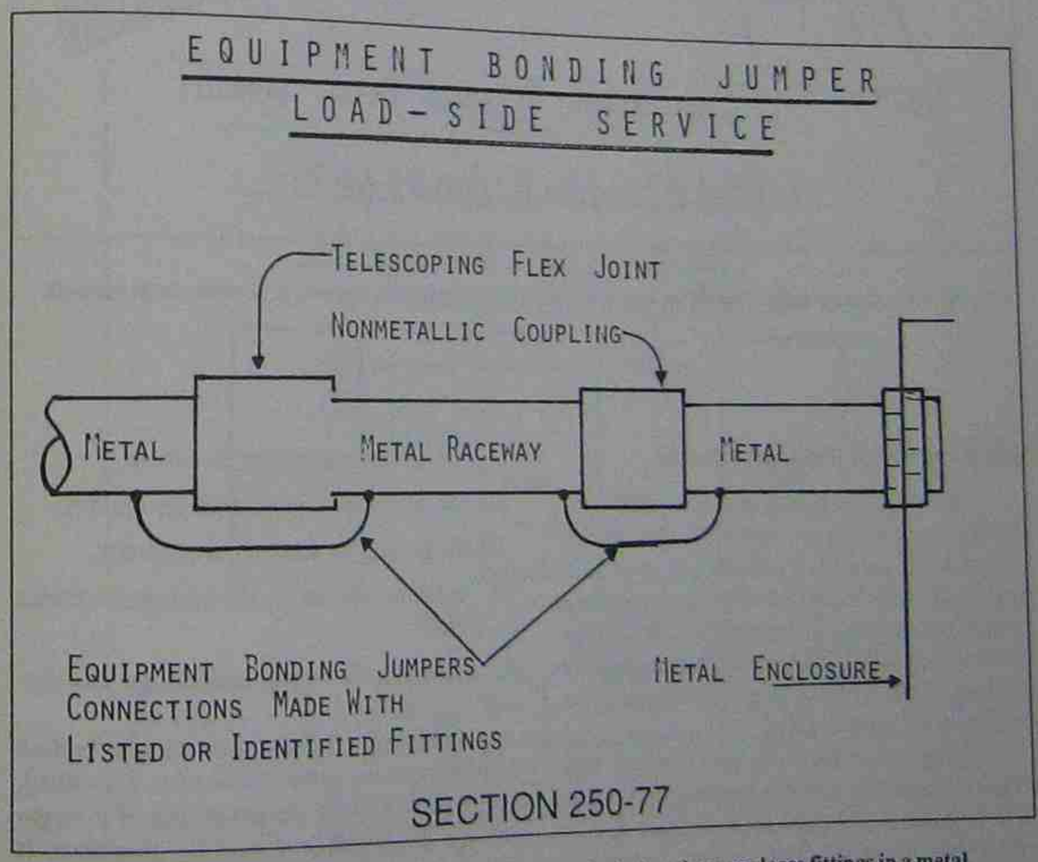

Fig. 11–35 An equipment bonding jumper is required when there are loose fittings in a metal raceway.

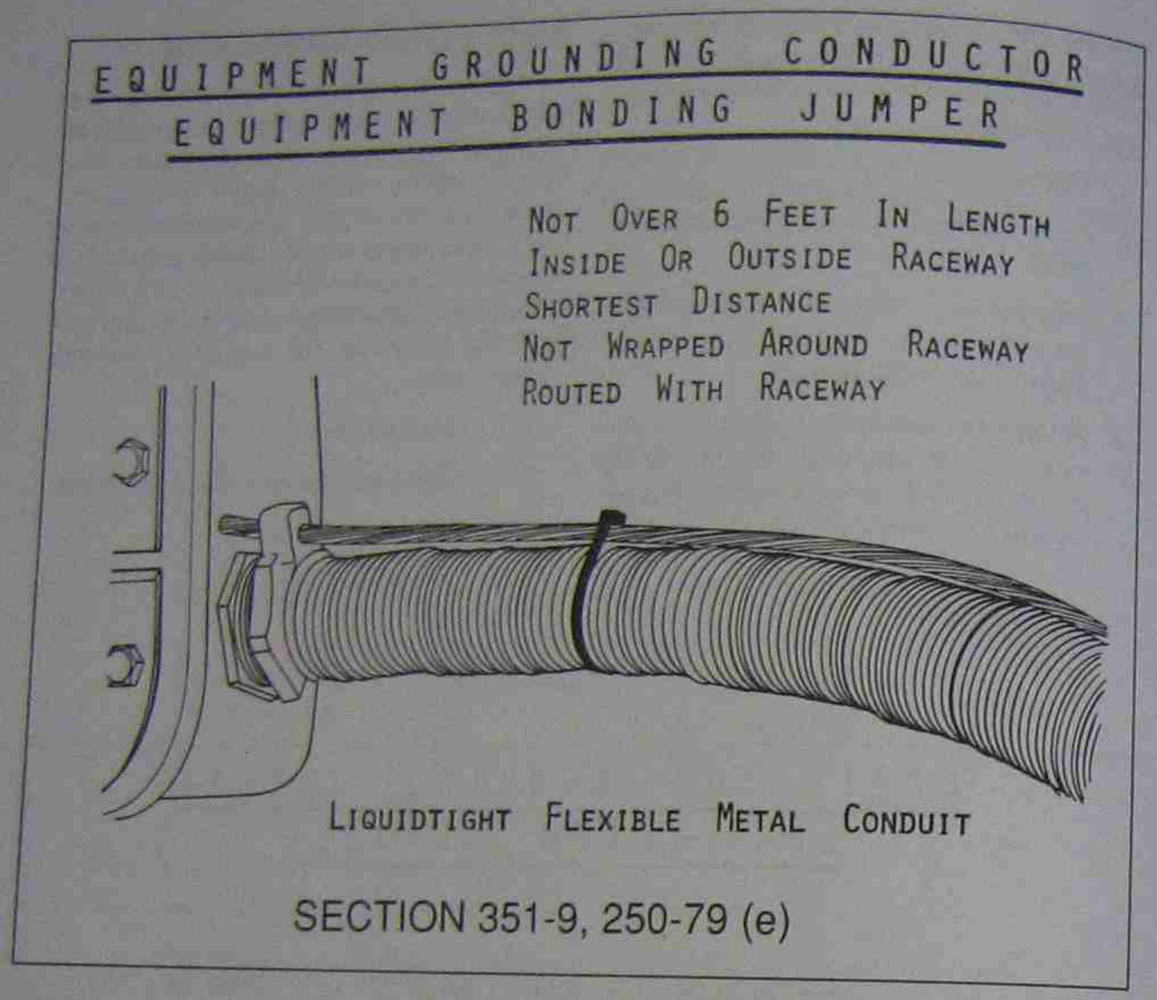

Fig. 11–36 Proper installation of an equipment bonding jumper with liquidtight flexible metal conduit.

Bonding Metal Piping Systems

Interior metal water piping systems are always required to be bonded to the service equipment (figure 11–37). In buildings of multiple occupancy (figure 11–38) where the water piping is part metal and part plastic, the exception to *Section 250-80(a)* DOES permit metallic sections of the water piping to be bonded to an enclosure that is grounded.

Piping other than the water piping that might become energized is required by *Section 250-80(b)* to be bonded to something that is effectively grounded. The section permits any of these piping systems to be bonded to:

1. the service equipment enclosure,
2. the grounded conductor at the service,
3. the grounding electrode conductor,
4. to one or more of the grounding electrodes used.

Question: Does this include the gas piping?

Answer: By the use of the phrase "which may become energized" in *Section 250-80(b)*, yes. It could include the gas piping. If it might become energized, it should be grounded. If there is a remote possibility the gas piping will become energized, it need not be grounded.

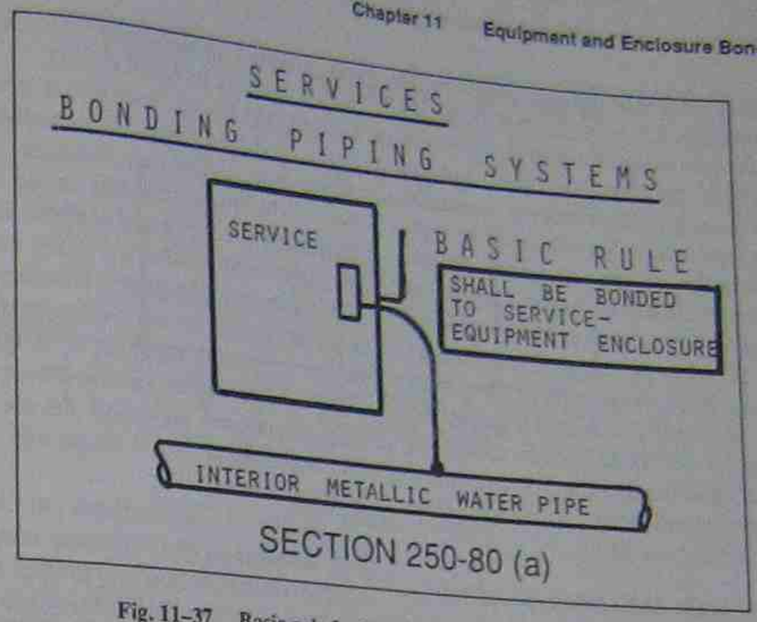

Fig. 11–37 Basic rule for bonding piping systems to service.

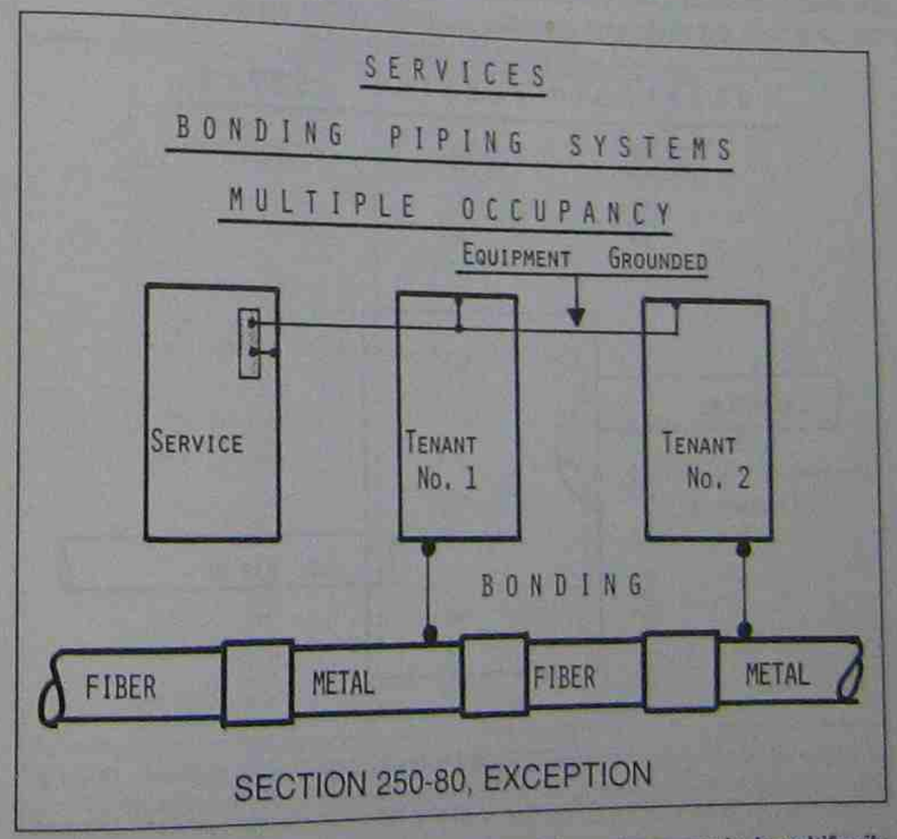

Fig. 11–38 An exception to the basic rule for bonding piping systems to service in multifamily dwellings with metal and nonmetal water piping.

Figure 11–39 illustrates a gas furnace with electrical controls. It is now possible for the gas line to the furnace to become energized by way of the electrical controls. The metal furnace would have to be grounded because it contains electrical equipment. In the process of grounding the furnace, the gas line is grounded. *Section 250-80(b)* permits this to be used as a grounding method. The same application would hold true for a gas dryer with an electric motor, a gas range with an electric light, and/or a receptacle or a gas heater with an electric blower. However, the Fine Print Note (FPN) to *Section 250-80(b)* contains a very good suggestion. It recommends bonding all piping and metal air ducts within the premises for additional safety.

Sizing Load Side of Service Bonding Jumpers

On the load side of the service, the equipment bonding jumpers are also part of the equipment grounding conductor. Therefore, they are sized the same way the equipment grounding conductor is sized. *Section 250-79(d)* requires this, according to *Table 250-95*.

Figure 11–40 illustrates a metal conduit being used for a feeder. The conduit enters the distribution switchgear through a concrete floor. The metal conduit is an equipment grounding conductor and needs to be bonded to the equipment ground bar in the switchboard. The necessary equipment bonding jumper is sized according to the overcurrent protective device protecting conductors in that conduit. *Table 250-95* (figure 11–41) shows that a 200-amp overcurrent protective device requires a No. 6 copper or No. 4 aluminum equipment bonding jumper.

Figure 11–42 illustrates parallel conductors installed in two separate conduits. The copper equipment bonding jumper is one continuous conductor connected to each metal conduit. The size is read directly from *Table 250-95* (figure 11–43). An 800-amp overcurrent protective device requires a No. 1/0 copper equipment bonding jumper.

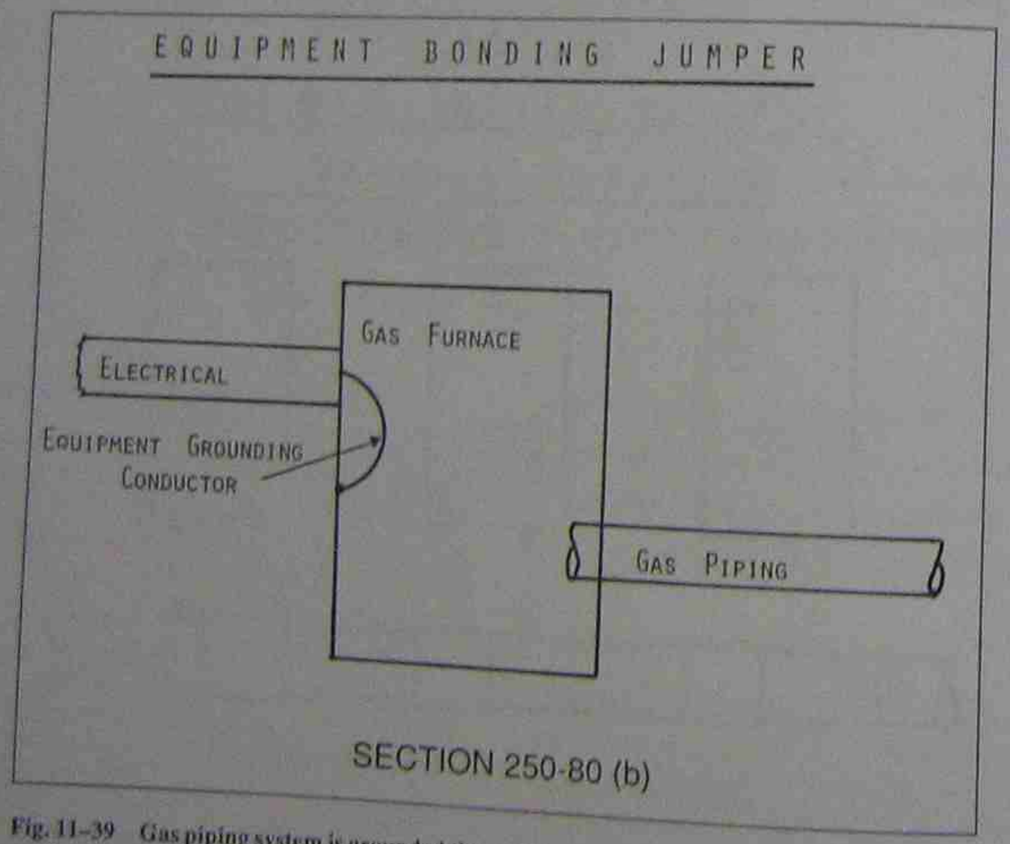

Fig. 11–39 Gas piping system is grounded through the metal continuity of the furnace and an equipment grounding conductor.

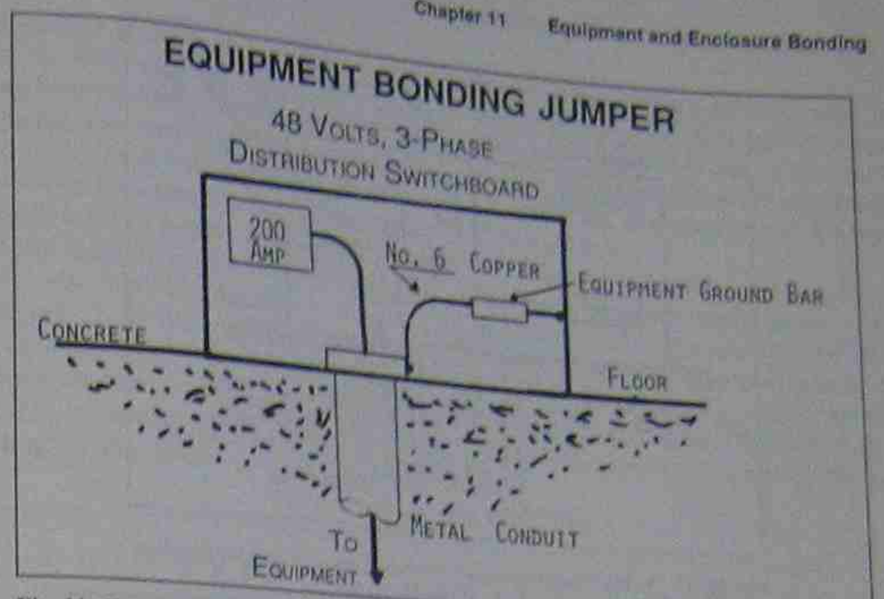

Fig. 11–40 Sizing the equipment bonding jumper for a feeder conduit used as an equipment grounding conductor.

70–116 NATIONAL ELECTRICAL CODE

Table 250-95. Minimum Size Equipment Grounding Conductors for Grounding Raceway and Equipment

Rating or Setting of Automatic Overcurrent Device in Circuit Ahead of Equipment, Conduit, etc., Not Exceeding (Amperes)	Size	
	Copper Wire No.	Aluminum or Copper-Clad Aluminum Wire No.*
15	14	12
20	12	10
30	10	8
40	10	8
60	10	8
100	8	6
200	6	4
300	4	2
400	3	1
500	2	1/0
600	1	2/0
800	0	3/0
1000	2/0	4/0
1200	3/0	250 MCM
1600	4/0	350 "
2000	250 MCM	400 "
2500	350 "	600 "
3000	400 "	600 "
4000	500 "	800 "
5000	700 "	1200 "
6000	800 "	1200 "

Fig. 11–41 Reading *Table 250-95* for the size of the equipment grounding conductor shown in **figure 11–40.** Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright ©, 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

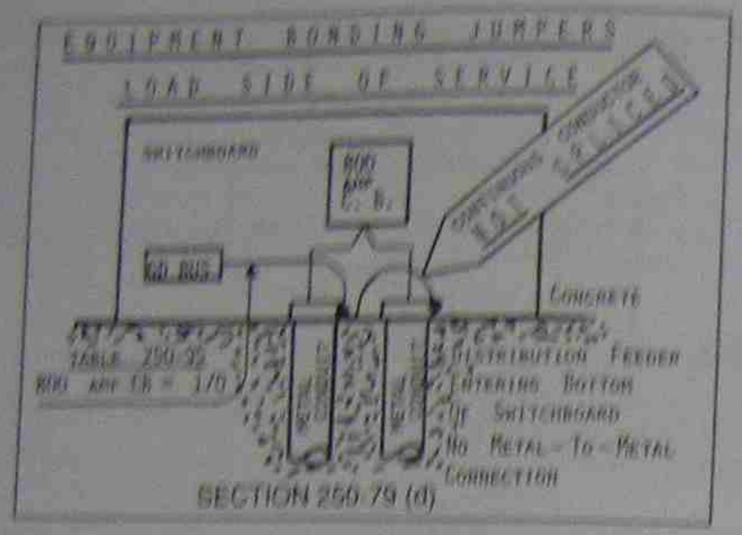

Fig. 11–42 Sizing a single equipment bonding jumper used for bonding two metal enclosures containing a parallel feeder.

Table 250-95 Minimum Size Equipment Grounding Conductors for Grounding Raceway and Equipment

Rating or Setting of Automatic Overcurrent Device in Circuit Ahead of Equipment, Conduit etc., Not Exceeding (Amperes)	Size	
	Copper Wire No.	Aluminum or Copper-Clad Aluminum Wire No.*
15	14	12
20	12	10
30	10	8
40	10	8
60	10	8
100	8	6
200	6	4
300	4	2
400	3	1
500	2	1/0
600	1	2/0
800	0	3/0
1000	2/0	4/0
1200	3/0	250 MCM
1600	4/0	350 MCM
2000	250 MCM	400 "
2500	350 "	600 "
3000	400 "	600 "
4000	500 "	800 "
5000	700 "	1200 "
6000	800 "	1200 "

Fig. 11–43 Reading the size of the bonding jumper shown in figure 11–42 from *Table 250-95*. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright ©, 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

A similar situation is illustrated in figure 11–44. Two separate copper equipment bonding jumpers, one from each metal conduit, are installed. The conductors in each conduit are backed up by an 800-amp breaker, therefore, each must be protected with a No. 1/0 copper equipment bonding jumper. Either installation, that shown in figure 11–42 or the one shown in figure 11–44, is permitted.

Figure 11–45 illustrates a copper equipment bonding jumper installed to maintain continuity between a cable tray and a switchboard. The equipment bonding jumper is sized according to the largest overcurrent device protecting any cable in the cable tray. In this case the largest overcurrent protective device is a 200-amp breaker. The size of the equipment bonding jumper is read directly from *Table 250-95* and is No. 6 copper or No. 4 aluminum (figure 11–46).

Figure 11–47 illustrates an equipment bonding jumper used in conjunction with flexible metal conduit (greenfield). The circuit is protected with a 60-amp overcurrent device. The size of the equipment grounding conductor is read directly from *Table 250-95* (figure 11–48), and is No. 10 copper or No. 8 aluminum.

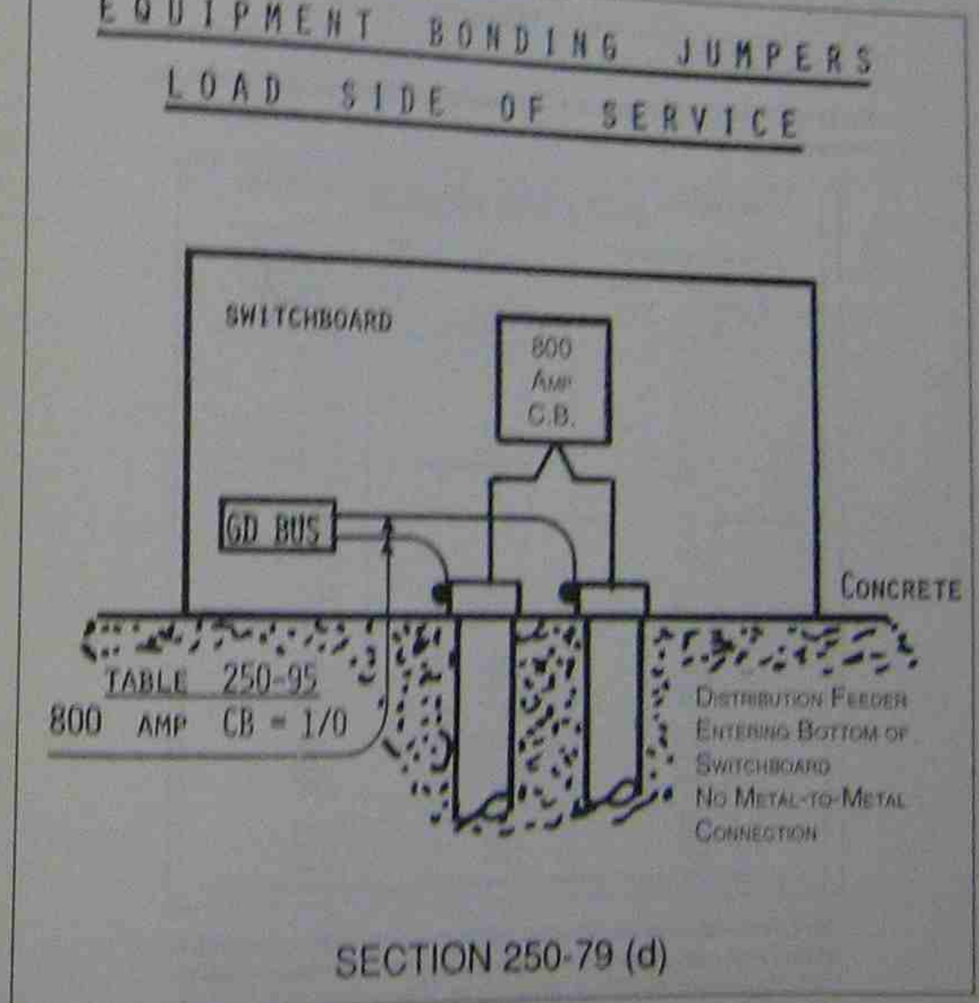

Fig. 11–44 Sizing two equipment bonding jumpers used for bonding two metal enclosures containing a parallel feeder.

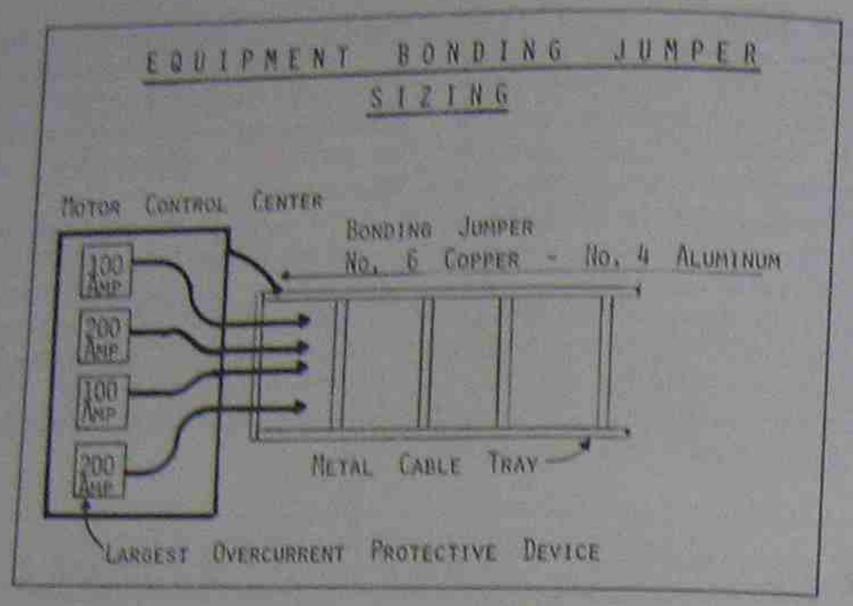

Fig. 11–45 Cable tray bonding to a metal enclosure is sized according to the largest overcurrent protective device protecting conductors installed in the cable tray.

Table 250-95. Minimum Size Equipment Grounding Conductors for Grounding Raceway and Equipment

Rating or Setting of Automatic Overcurrent Device in Circuit Ahead of Equipment, Conduit, etc., Not Exceeding (Amperes)	Size	
	Copper Wire No.	Aluminum or Copper-Clad Aluminum Wire No.*
15	14	12
20	12*	10
30	10	8
40	10	8
60	10	8
100	8	6
200	6	4
300	4	2
400	3	1
500	2	1/0
600	1	2/0
800	0	3/0
1000	2/0	4/0
1200	3/0	250 MCM
1600	4/0	350 "
2000	250 MCM	400 "
2500	350 "	600 "
3000	400 "	600 "
4000	500 "	800 "
5000	700 "	1200 "
6000	800 "	1200 "

Fig. 11–46 Reading the size of the equipment bonding jumper shown in figure 11–45 from *Table 250-95*. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright ©, 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

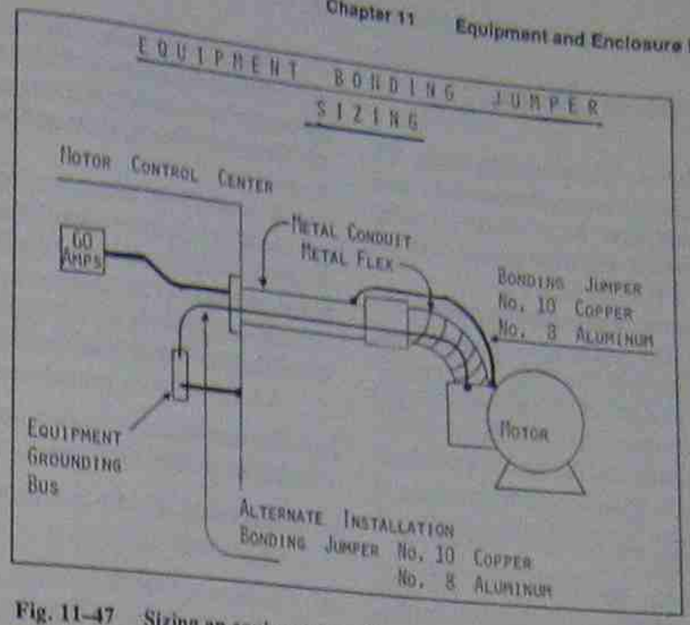

Fig. 11–47 Sizing an equipment bonding jumper used with flexible metal conduit.

Table 250-95. Minimum Size Equipment Grounding Conductors for Grounding Raceway and Equipment

Rating or Setting of Automatic Overcurrent Device in Circuit Ahead of Equipment, Conduit, etc., Not Exceeding (Amperes)	Size	
	Copper Wire No.	Aluminum or Copper-Clad Aluminum Wire No.*
15	14	12
20	12	10
30	10	8
40	10	8
60	10	8
100	8	6
200	6	4
300	4	2
400	3	1
500	2	1/0
600	1	2/0
800	0	3/0
1000	2/0	4/0
1200	3/0	250 MCM
1600	4/0	350 "
2000	250 MCM	400 "
2500	350 "	600 "
3000	400 "	600 "
4000	500 "	800 "
5000	700 "	1200 "
6000	800 "	1200 "

Fig. 11–48 Reading the size of the equipment bonding jumper shown in figure 11–47 from *Table 250-95*. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright ©, 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

Bonding Grounding Electrode Systems

The telephone company, the cable TV company, and the computer companies often feel they should have an isolated grounding electrode. However, this is not permitted by the Code.

More often than not, the telephone company seeks out the existing grounding electrode system and bonds to it. The cable TV company very often drives a ground rod of their own and establishes a separate grounding electrode system. Their reason is that the neutral feeds back into their system. This is possible but there is equipment that can be installed that will prevent a neutral feedback.

The computer people want to establish their own isolated grounding electrode system and not be connected to the premises grounding electrode system. Their reason is that the power system's electricity is too dirty and too noisy.

The Code permits these entities to establish their own grounding electrode system, but no matter how many grounding electrode systems are established, they shall all be bonded together.

Figure 11–49 illustrates three separate grounding electrodes established. There is a potential difference between each of the electrodes and there is an impedance between each of the electrodes when there is potential difference. There is a hazard and there is current flow.

A simple Ohm's law calculation might be:

The impedance between two of the electrodes is 200 ohms.

There is a half-amp trickle of current flow.

Ohm's law $E = I Z$

$E = .5 \times 200$

$E = 100$ volts

Under fault, lightning, or surge conditions, the current value could increase, Ohm's law would still hold true, and the voltage could be extremely high. When the separate grounding electrodes are not connected together, a very dangerous and hazardous condition is built into the system.

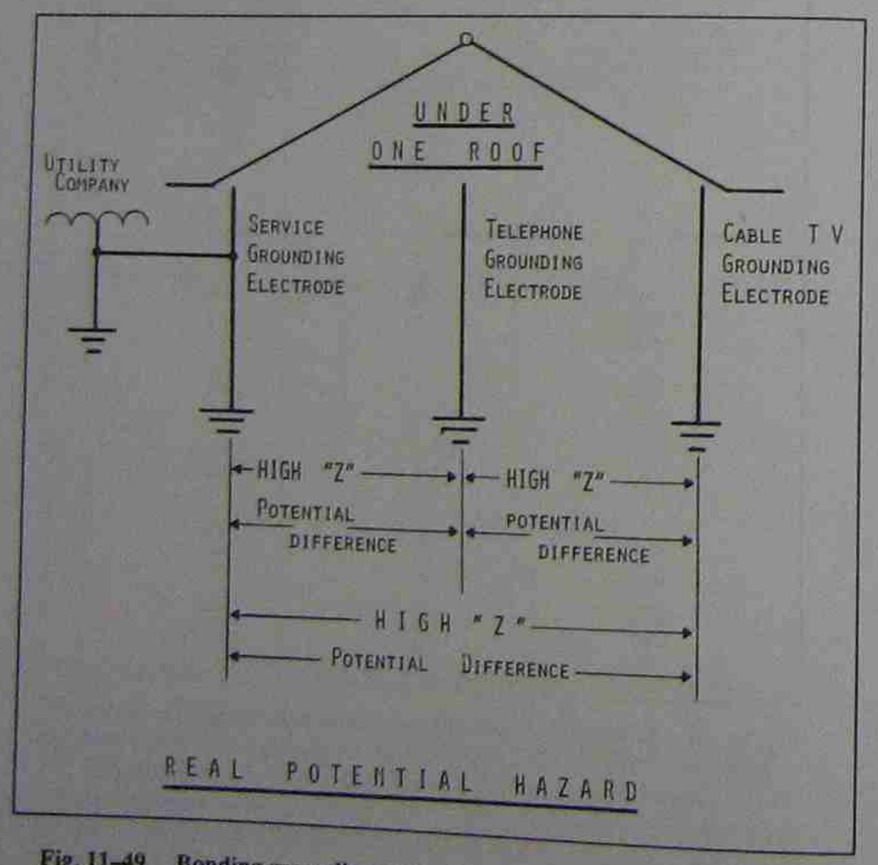

Fig. 11–49 Bonding grounding electrodes when more than one is installed.

When more than one electrode system is installed, *Section 250-81* requires all grounding electrodes to be bonded together. *Section 250-71(b)* (figure 11–50) requires that a means of bonding be made available. *Section 250-71(b)* sets the requirements for bonding to other systems.

1. The purpose is to maintain zero potential between all metal equipment enclosures.
2. The availability of the grounding is required only at dwelling units.
3. The means provided shall be external to the enclosure. The means shall be accessible.
4. It shall be provided by one of the following means:
   a. Exposed metallic service raceway,
   b. Exposed grounding electrode conductor,
   c. Approved means for external connection of a bonding or grounding conductor to the service raceway or equipment.

The FPN to *Section 250-71(b)* (figure 11–51) suggests that the bonding connection be:

1. No. 6 copper
2. At least 6 inches long
3. Bonded to the service raceway or equipment at one end
4. Accessible on the outside of the wall of a dwelling

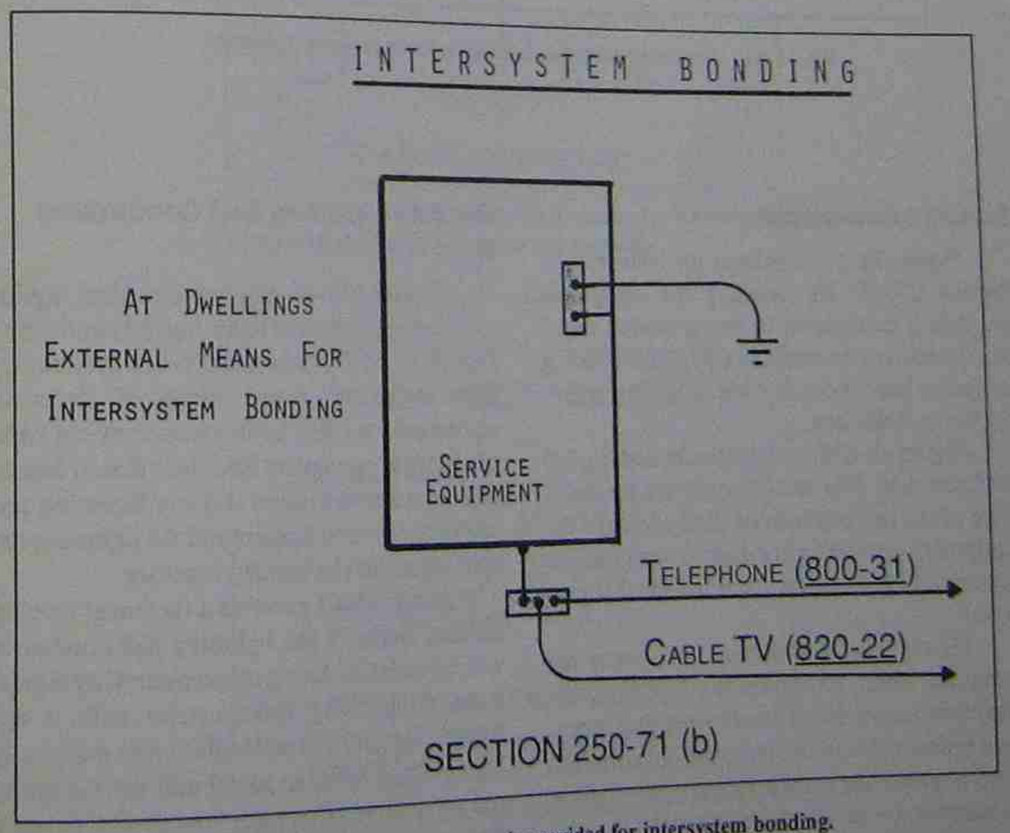

Fig. 11–50 An external means is provided for intersystem bonding.

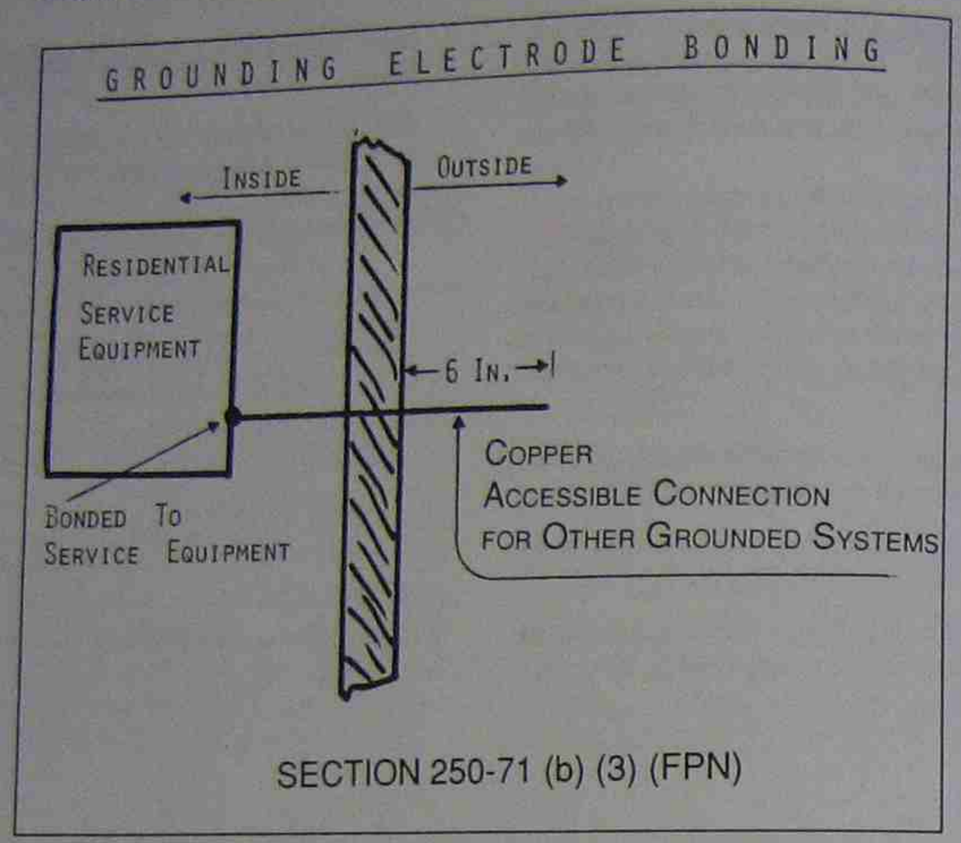

Fig. 11–51 Suggested accessible connection for intersystem bonding.

Bonding Receptacles

Figure 11–52 illustrates the basic rule in *Section 250-74* for bonding the equipment grounding connection to the grounded metal box. It requires the use of an equipment bonding jumper to bond the receptacle grounding terminal to the metal box.

Figure 11–53 illustrates Exception No. 1 to the basic rule. The exception allows the metal yoke of the receptacle to be used as part of the equipment grounding conductor. Note that the yoke must be listed or identified for that purpose.

Figure 11–54 illustrates the exception contained within Exception No. 1. This exception prohibits the use of a cover-mounted receptacle unless the box and cover combination are listed as providing satisfactory ground continuity between the box and the receptacle.

Bonding Lightning Rod Conductors and Electrodes

Section 250-46 requires electrical equipment to be kept clear of lightning rod conductors (figure 11–55). When metal raceways, equipment enclosures, metal frames of electrical equipment, or other noncurrent-carrying parts of electrical equipment have less than 6 feet of clearance between them and any lightning rod conductors, the equipment and the lightning rod conductor shall be bonded together.

Reason: This prevents a flashover (arcing contact) between the lightning rod conductor and the metal enclosing current-carrying equipment. A lightning strike carries with it extremely high voltage and builds up an extremely high voltage between metal and the lightning rod conductors. This high voltage can cause a flashover and result in considerable damage.

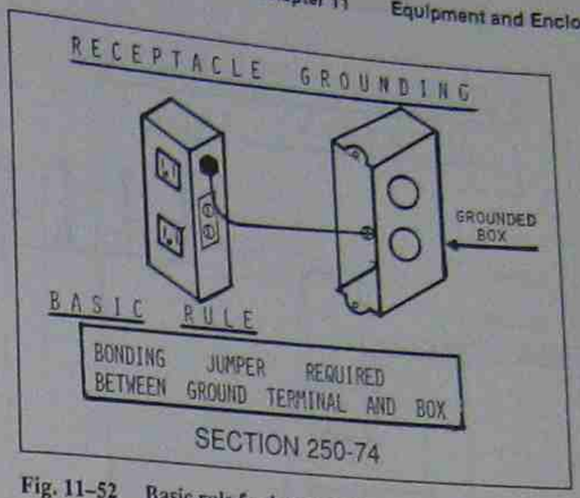

Fig. 11–52 Basic rule for bonding the equipment grounding connection to a receptacle.

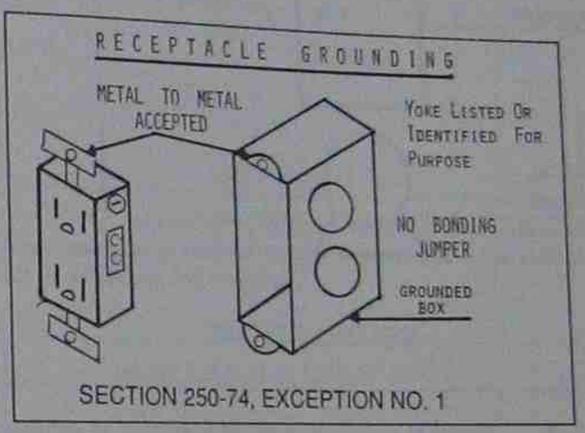

Fig. 11–53 Exception No. 1 to the basic rule for bonding the equipment grounding connection to a receptacle.

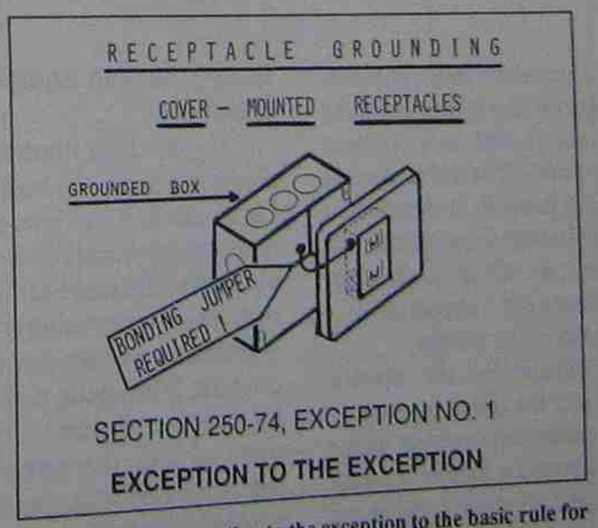

Fig. 11–54 An exception to the exception to the basic rule for bonding the equipment grounding connection to a receptacle.

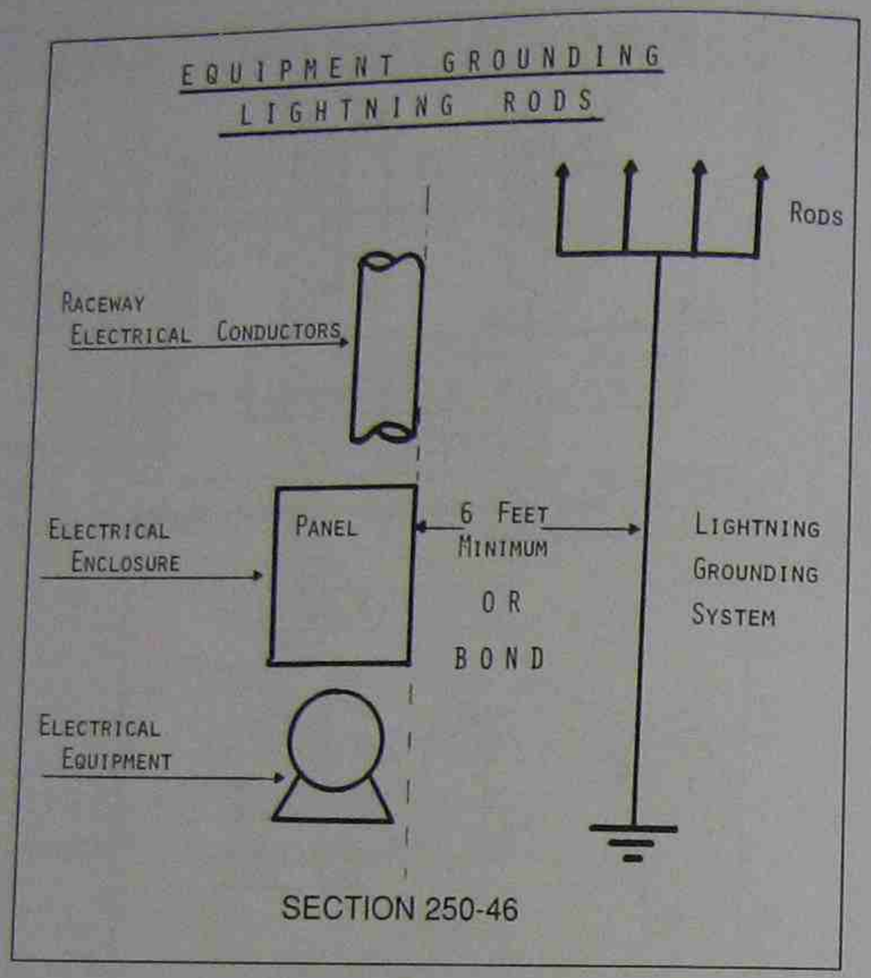

Fig. 11–55 Electrical equipment must be kept clear of lightning rod conductors.

Figure 11–56 illustrates electrical equipment installed less than 6 feet from a lightning rod conductor and shows that an equipment bonding jumper is required. It would be sized as an equipment bonding jumper. In the illustration, the panel close to the lightning rod conductor is protected by a 400-amp breaker. *Table 250-95* requires a No. 3 copper or No. 1 aluminum equipment bonding jumper.

Figure 11–57 illustrates the service grounding electrode and the lightning grounding electrode being connected together with a bonding jumper. This bonding jumper is part of the grounding electrode conductor and is the same size as the grounding electrode conductor.

Establishing an Equipotential Plane for Livestock

Figure 11–58 illustrates the problem that occurs in agricultural buildings used for housing livestock. When wire mesh or other metal conducting materials are buried in the concrete, a potential difference can be detected between metal items in the vicinity. The illustration uses voltmeters to indicate that a potential difference can exist. When cattle stand on the concrete and brush against or come in contact with any of the metal surfaces, they receive an electric shock. And as the FPN to *Section 547-8(b)* indicates, it could alter animal behavior or productivity. To combat the problem, an "equipotential plane" is

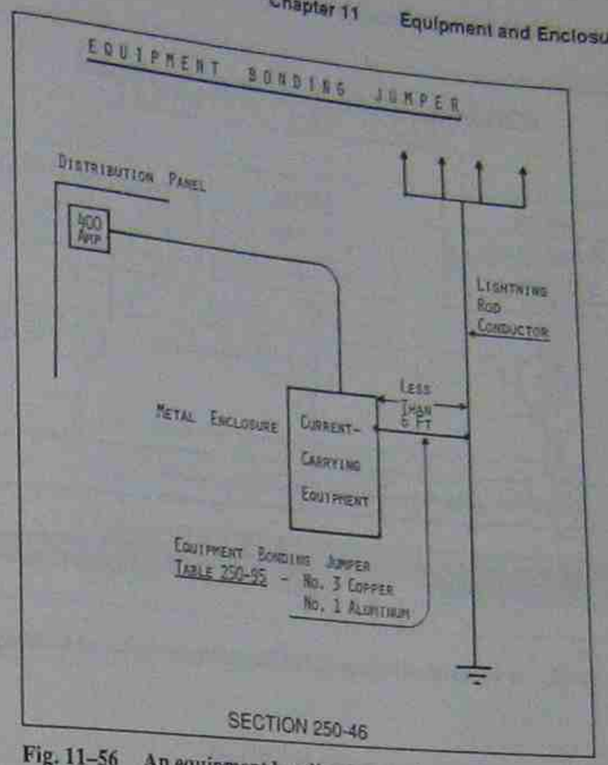

Fig. 11–56 An equipment bonding jumper is required when the metal enclosure for electrical equipment is installed within 6 feet or less of a lightning rod conductor.

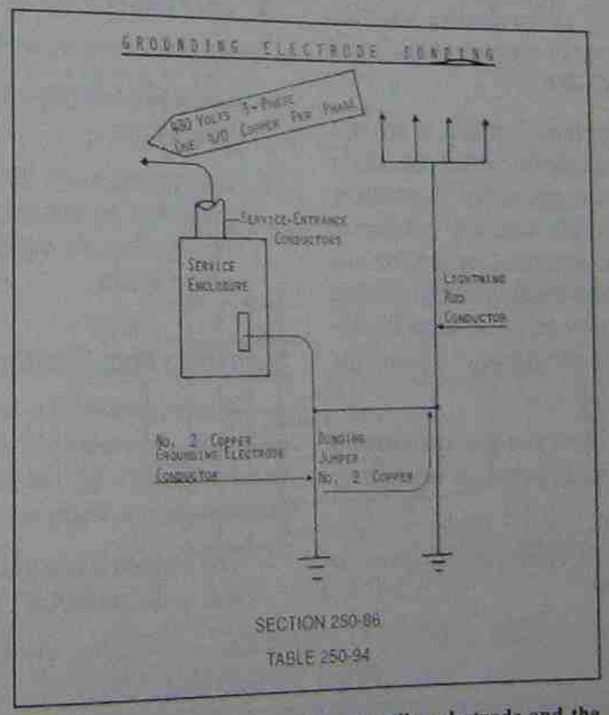

Fig. 11–57 Bonding the service grounding electrode and the lightning grounding electrode together is permitted.

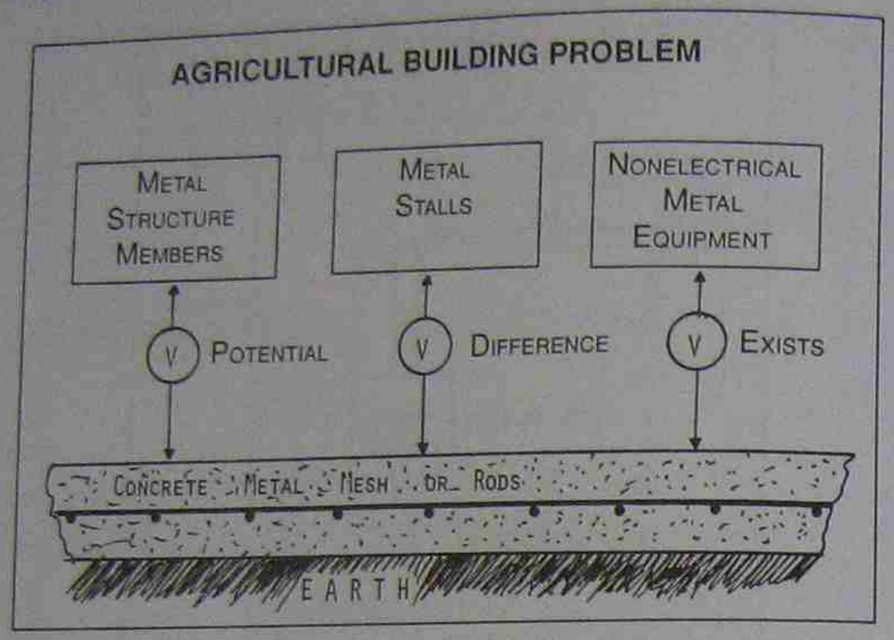

Fig. 11–58 A problem with potential difference in agricultural buildings.

created by bonding all conductive materials together. A definition of *equipotential plane* is given in *Section 547-8(b)*.

Quote – "An equipotential plane is an area where a wire mesh or other conductive elements are embedded in concrete, bonded to all adjacent conductive equipment, structures, or surfaces and connected to the electrical grounding system to prevent a difference in voltage from developing within the plane."*

Figure 11–59 illustrates the equipotential plane with the following points, as required by *Section 547-8(b)*:

1. All metal surfaces bonded to metal mesh or rods in concrete
2. No. 8 copper bonding conductor
3. Insulated, covered, or bare conductor
4. Connected to equipment grounding electrode system
5. Connections made by means of pressure connectors or clamps of brass, copper, copper alloy, or equally substantial approved means

Swimming Pool Bonding Grid

The purpose of the bonding grid is explained in *Section 680-22* (FPN) and is illustrated in figure 11–60. The FPN makes two very important points. These are:

1. The purpose is to eliminate voltage gradients in the pool area.

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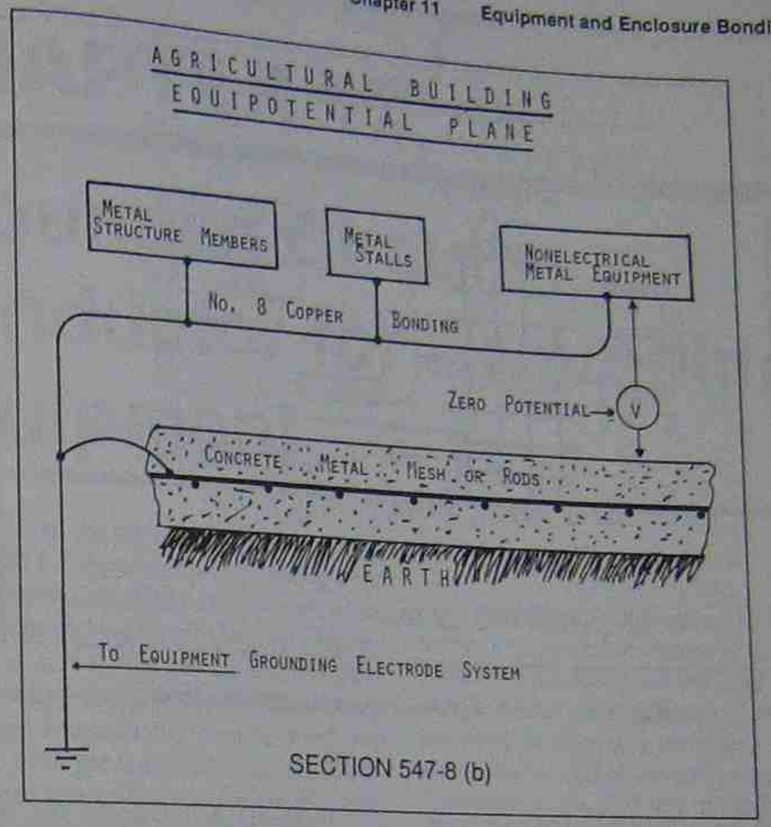


Fig. 11–59 Equipotential plane in agricultural buildings.

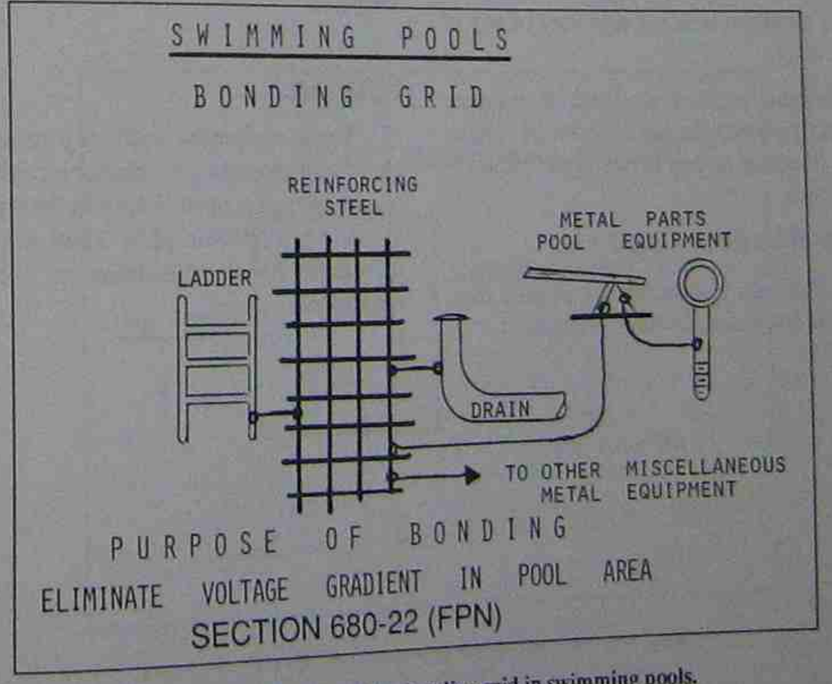


Fig. 11–60 Purpose of the bonding grid in swimming pools.

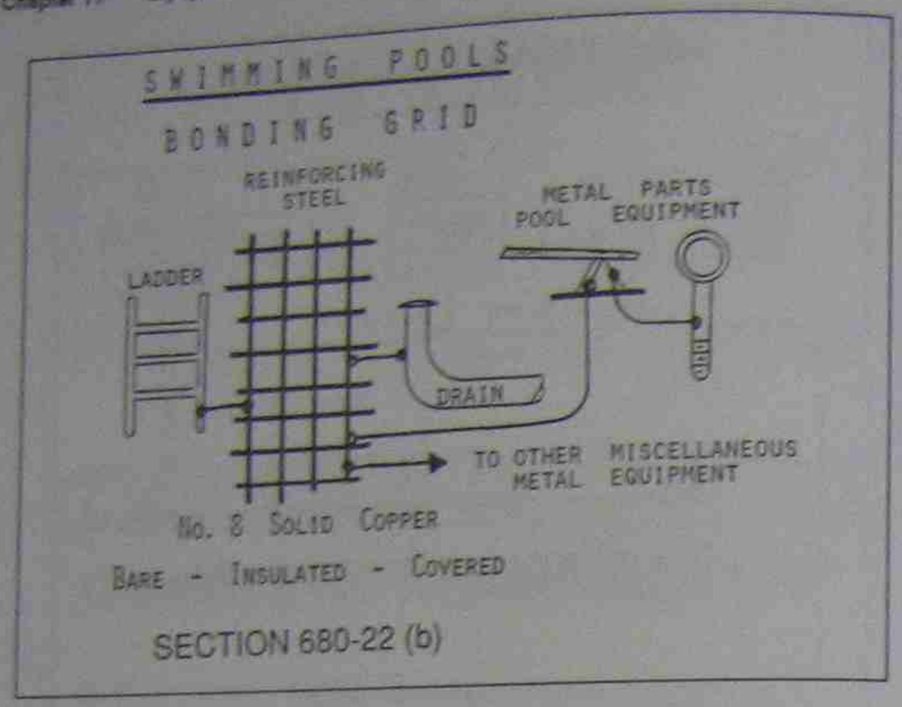


Fig. 11–61 Bonding grid requirements in swimming pools.

2. The grid is not required to be connected back to an equipment grounding conductor or a grounding electrode.

The common bonding grid may be any of the following:

1. Structural reinforcing steel of concrete pools with tie wire permitted to be used as the bonding means between the reinforcing rods
2. Wall of bolted or welded pools
3. Solid copper conductor not smaller than No. 8; insulated, covered, or bare

Figure 11–61 illustrates the reinforcing steel being used as the common grounding grid with all metal bonded to the grid with No. 8 solid copper.

SUMMARY

Using equipment bonding jumpers in the equipment grounding conductor circuit is good insurance against open circuits in the equipment grounding conductor path. They are a good investment for the protection of people and equipment.

CHAPTER 12

Grounded Circuit Conductor for Grounding Equipment

The use of the grounded circuit conductor (the neutral) for the equipment grounding conductor is almost unlimited on the line side of the service disconnecting means but is very limited on the load side of the service disconnecting means. (For a review of the line and load sides of the service disconnecting means, check figure 11–4 in the previous chapter.) This limitation is stated several times in *Article 250*, starting with *Section 250-23* (figure 12–2).

THE BASIC RULE

The basic rule in *Section 250-23* prohibits using the grounded conductor as the equipment grounding conductor on the load side of the service disconnecting means. This rule is followed by an exception permitting very limited use of the neutral as the equipment grounding conductor on the load side of the service.

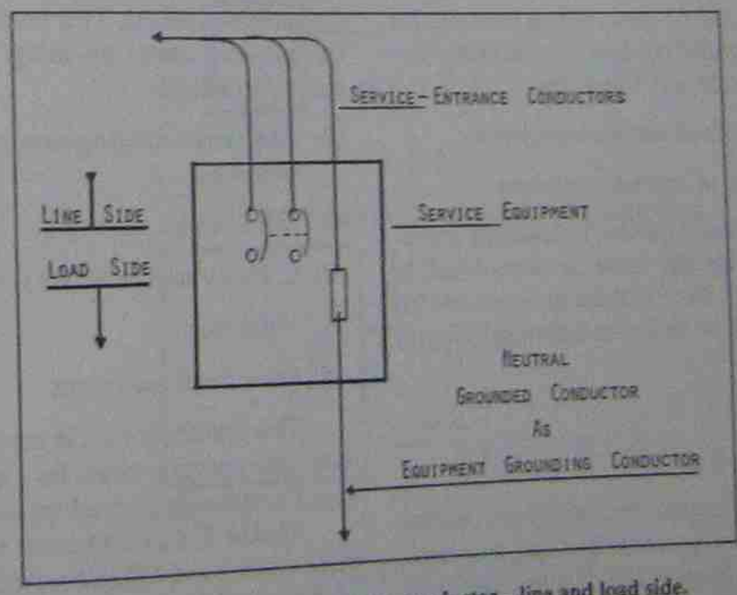


Fig. 12–1 Equipment grounding conductor—line and load side.

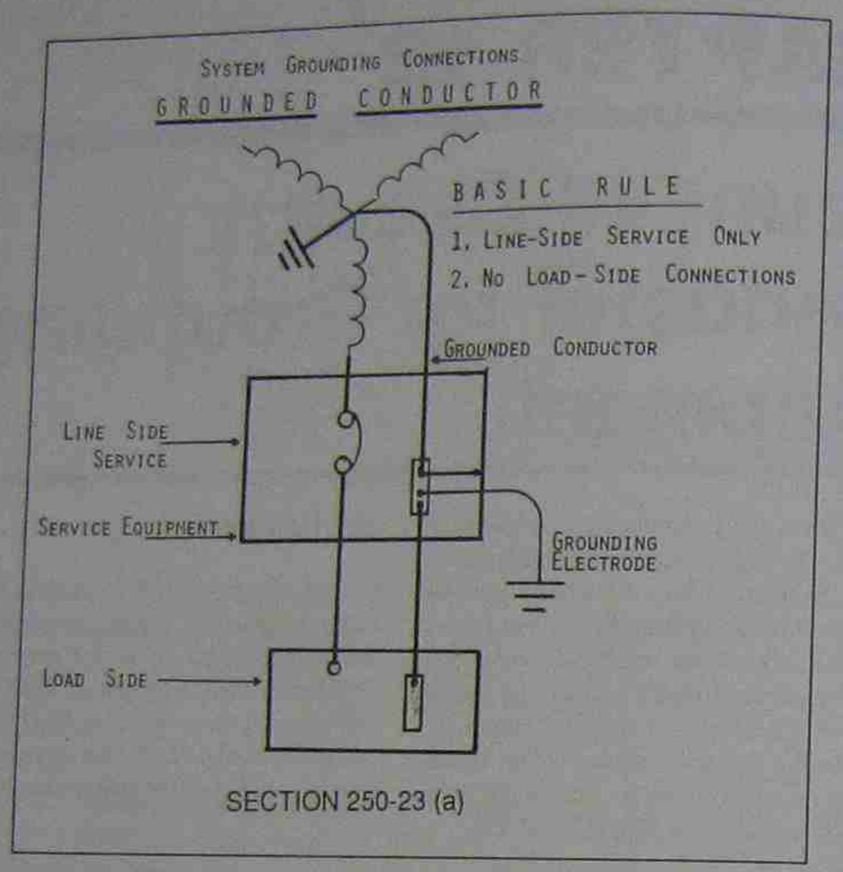


Fig. 12–2 The basic rule for use of neutral as the equipment grounding conductor.

Section 250-61 looks at two locations for using the grounded conductor as the equipment grounding conductor. These are:

1. Supply side of service equipment
2. Load side of service equipment

This section is quickly followed by exceptions, which are the same as those listed in *Section 250-23*. Each of these divisions and the exceptions will be looked at individually in this chapter.

SUPPLY-SIDE USE

The Code uses the term *supply side*, and the field term generally used is *line side*; they mean the same thing. *Section 250-61(a)* permits using the grounded conductor for grounding equipment on the supply or line side of the service disconnecting means. This permits grounding the following items by using the grounded (neutral) conductor:

1. Noncurrent-carrying metal parts of service equipment
2. Metal service raceways
3. Current transformer (CT) can
4. Meter base
5. Other metal enclosures

This also applies to the supply side of the main disconnecting means for a separate building or a separately derived system.

Section 250-24 addresses separately derived systems and will be covered in chapter 16 of this text. This actually puts very little limitation on the use of the neutral for grounding metal enclosures for current-carrying equipment on the supply side. Some of the enclosures used in conjunction with service equipment, for which the neutral can be used to ground, are a meter base, weather head, CT can, auxiliary gutter, wireway, or any section of metal enclosure for the service-entrance conductors (figure 12–3).

The second place that the grounded conductor is permitted to be used to ground equipment (figure 12–4) is on the supply side of the disconnecting means of the second building, when two buildings are served by one service. The example in figure 12–4 shows the service disconnecting switch in building number two bonded to the neutral conductor.

LOAD-SIDE USE

The use of the grounded conductor for equipment grounding on the load side of the service disconnecting means is very limited. The basic rule in *Section 250-61(b)* prohibits using the grounded conductor (neutral) for grounding equipment on the *load side* of the following locations:

1. The service disconnecting switch
2. The disconnecting switch for a separately derived system
3. The main disconnecting means for a separate building

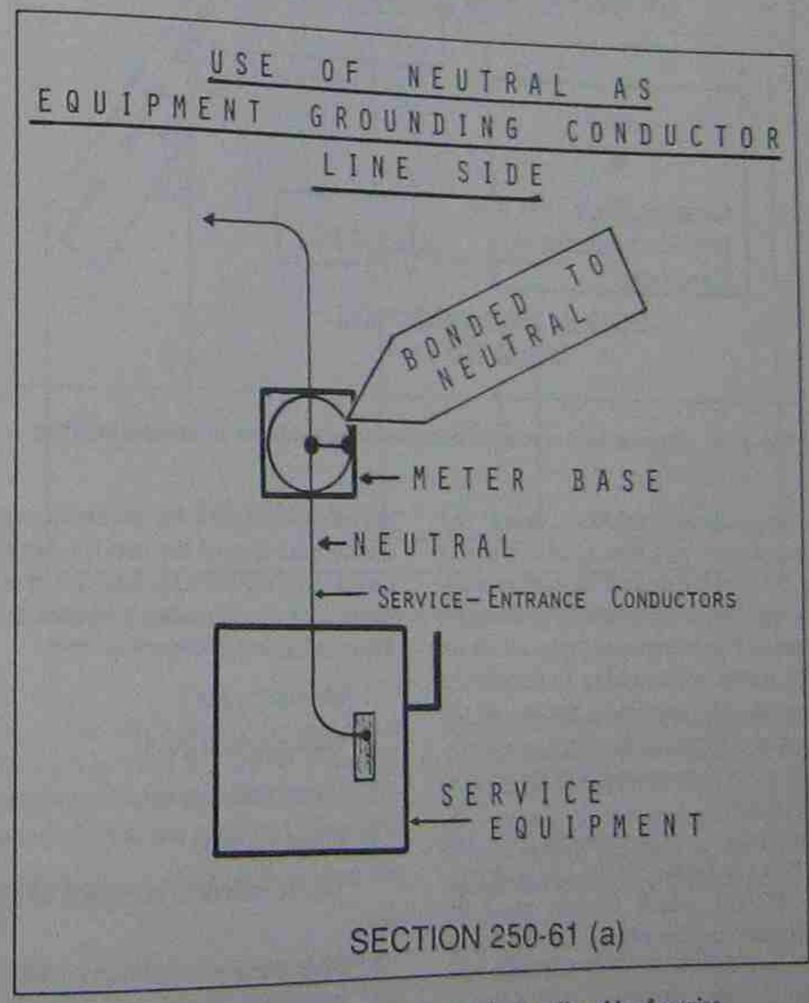


Fig. 12–3 Neutral used to ground meter base on line side of service.

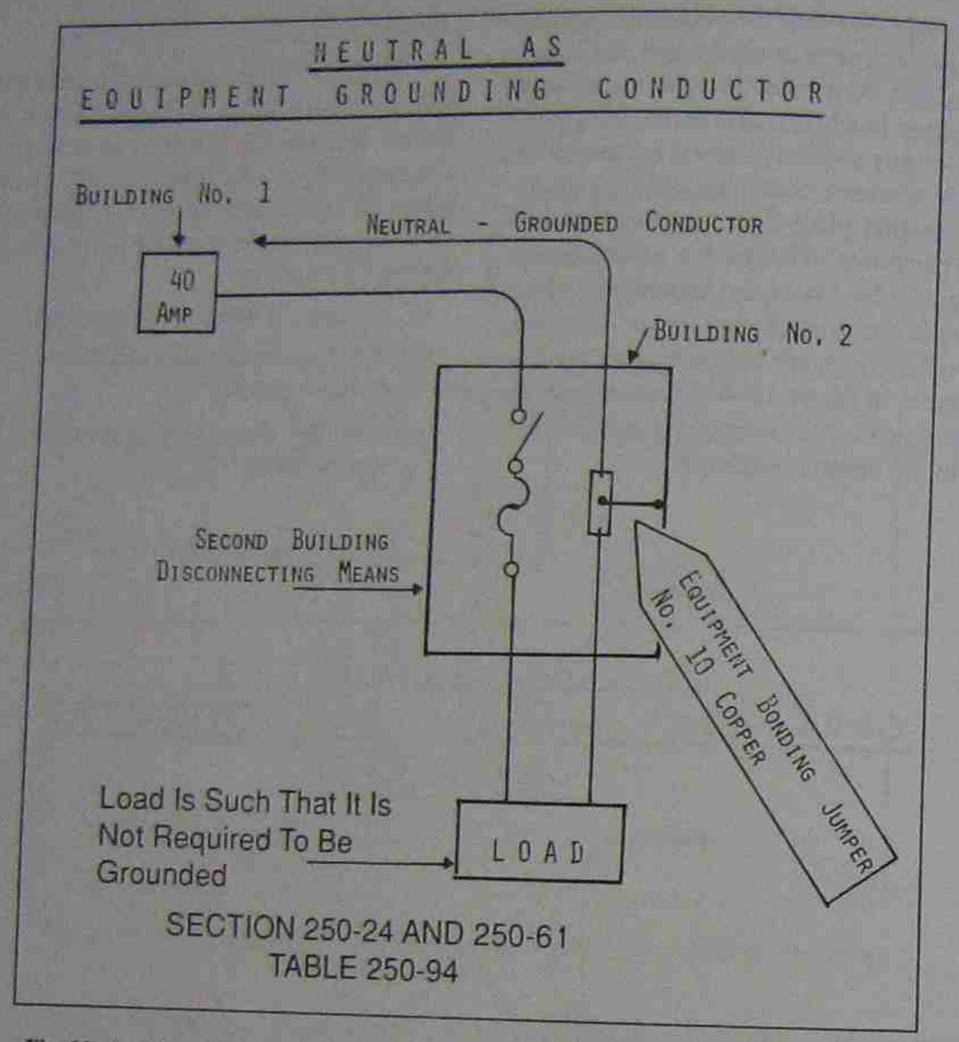


Fig. 12–4 Neutral used as an equipment grounding conductor to a second building.

This regulation prohibits using the grounded conductor as a means of equipment grounding. Should the neutral be used promiscuously for equipment grounding, there could be a multitude of unintentional paths set up for electrons to travel on, resulting in circulating ground currents. By regulating the use of the neutral as an equipment grounding conductor, there is more control exercised over the path the electrons will travel.

Exception No. 3 in *Section 250-23(a)* and Exception No. 1 in *Section 250-61(b)* both refer to *Section 250-60*, which permits using the grounded conductor (the neutral) as the equipment grounding conductor (figure 12–5). *Section 250-60* permits the use of the neutral or grounded conductor for grounding equipment on the load side of the service disconnecting means. It also gives a specific list of equipment permitted to be grounded by use of the neutral. This list includes:

1. Electric ranges
2. Wall-mounted ovens
3. Counter-mounted cooking units
4. Clothes dryers

This section does not apply to the following:

1. Mobile homes
2. Recreation vehicles

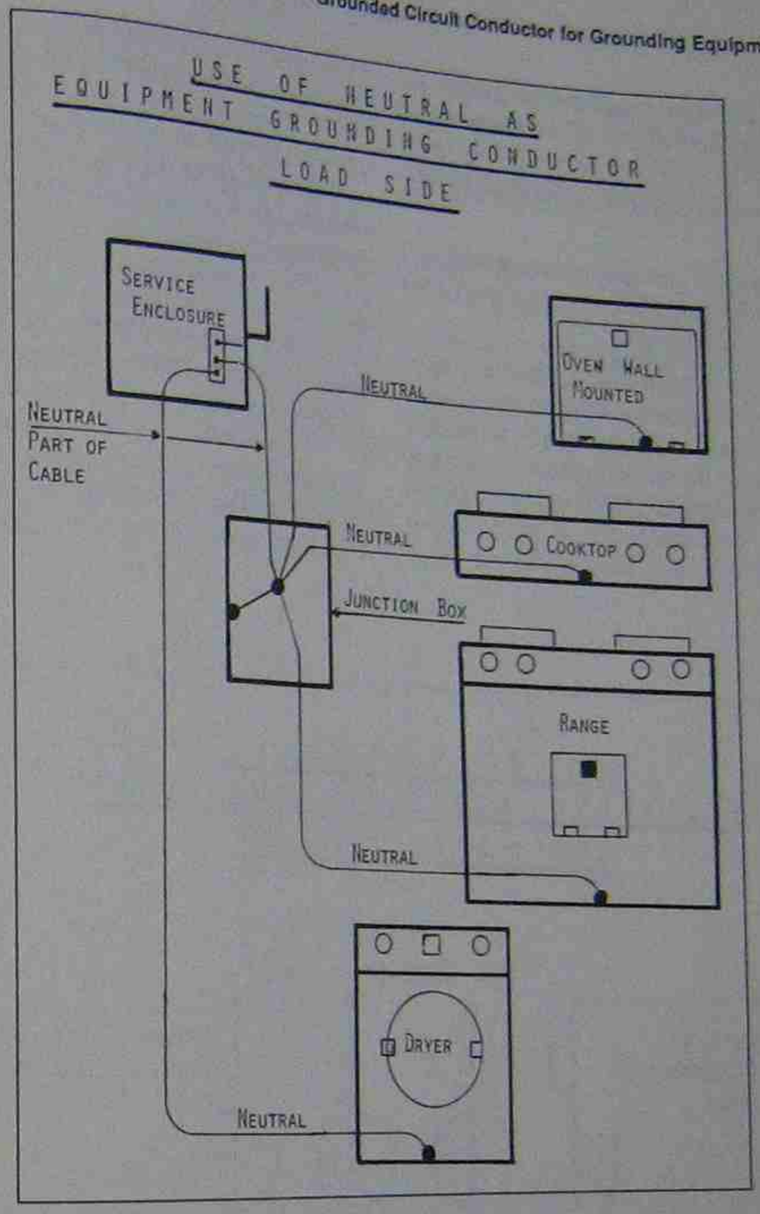


Fig. 12–5 Neutral used as equipment grounding conductor for grounding electrical cooking equipment and dryer.

Section 250-60(a) is very specific about the supply circuit when the neutral is used to ground an electric range or clothes dryer. Actually, only two circuits are permitted. These are:

1. 120/240-volt, single-phase, three-wire circuit
2. 120/208-volt, single-phase, three-wire circuit derived from a three-phase, four-wire system

The requirement of single phase and the lower voltage almost limits the use of this exception to residential installation. In addition to the circuit requirement, all the following conditions must be met before the neutral can be used as the equipment grounding conductor.

1. The grounded conductor is not smaller than No. 10 copper or No. 8 aluminum.

2. The grounded conductor is insulated unless part of Type SE service-entrance cable.
3. The circuit originates at the service equipment.
4. Grounding contacts of receptacles furnished as part of the equipment are bonded to the equipment.

Looking at *Table 250-95*, No. 10 copper or No. 8 aluminum is permitted when the overcurrent protective device is not over 60 amps. This is applicable to the majority of electric ranges or cooking equipment installed in residential occupancies. Once again, note in point 2 above how there is an indication of the use being limited to residential occupancies. This occurs by the use of an insulated conductor or a conductor that is covered in a service-entrance cable. The ground path for the electrons to travel on is also controlled. When point 3 above requires the circuit to originate in the service equipment, it eliminates any situations where the equipment is fed from a distribution panel. An example of point 4 is an electric range with built-in receptacles. The grounded contact of the receptacle must be bonded to the range before the range can be grounded with the neutral conductor.

There is encouragement here to use cord- and plug-connected appliances with an equipment grounding means built into the cord, so that when a nonqualified person moves the equipment from house to house, there is no hard wiring to be done. The installation of an equipment grounding conductor is not left to an unqualified person.

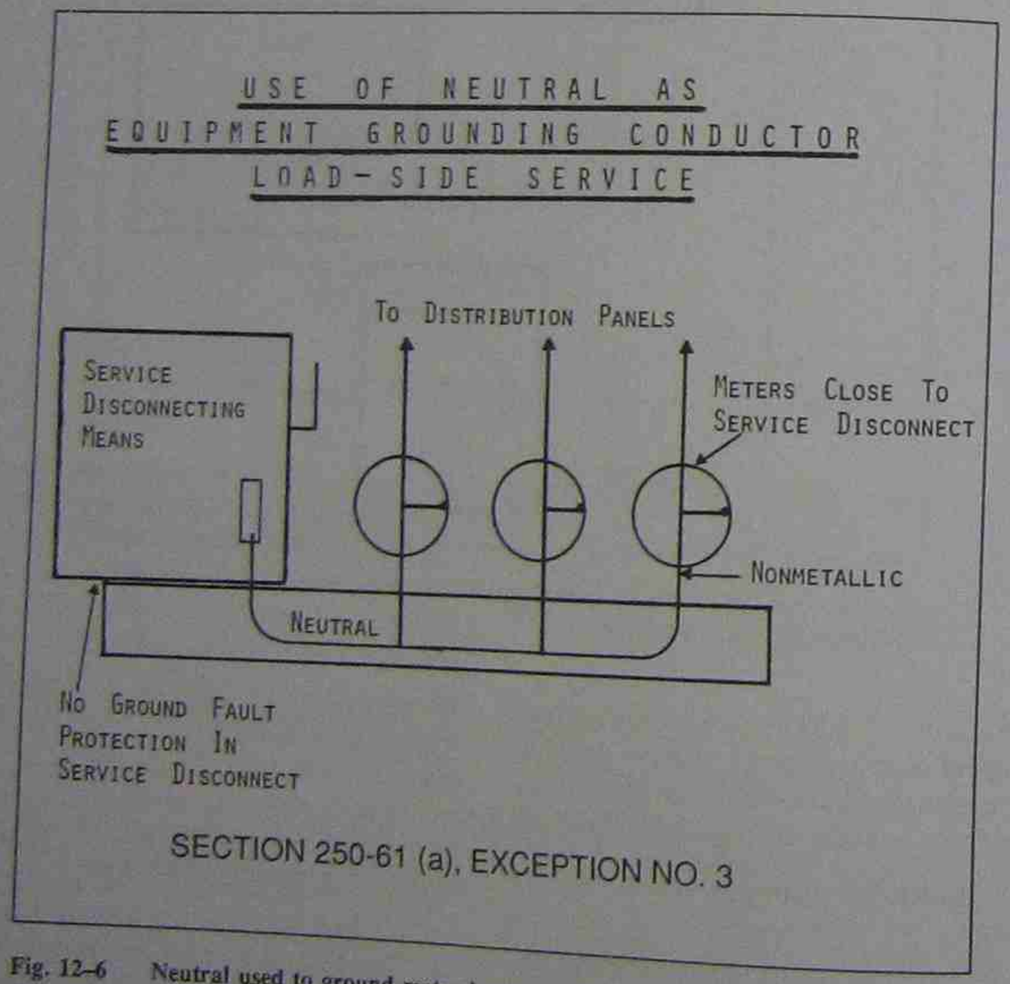


Fig. 12–6 Neutral used to ground meter bases located on load side and close to service disconnecting means.

Section 250-61, Exception No. 3 is illustrated in figure 12–6. It permits the grounded conductor to be used as the equipment grounding conductor on the load side of the service equipment to ground meter enclosures on the load side of the service disconnect, when both of the following conditions are met:

1. No service ground-fault protection is installed.
2. All meter enclosures are located near the service disconnect.

Such an installation could be used for a multifamily dwelling with each unit individually metered, or for a small building with each unit individually metered.

SUMMARY

This chapter has shown the mixed use of a grounded conductor, intentionally grounded and installed as a current-carrying circuit conductor. Under certain conditions this grounded conductor serves a twofold purpose. It is the grounded, current-carrying circuit conductor and the equipment grounding conductor.

CHAPTER 13

Equipment and Enclosure Grounding

When an enclosure or a raceway is grounded, as the definition of *grounded* states, the enclosure or raceway is connected to earth in some way. When effectively connected to earth, it becomes part of the overall grounding system and the metal enclosure will have zero potential to ground as long as it remains effectively connected to ground.

WHY GROUND METAL ENCLOSURES AND EQUIPMENT?

Once again the question is asked, Why ground conductive materials and enclosures of electrical equipment? The answer is illustrated in figure 13–2.

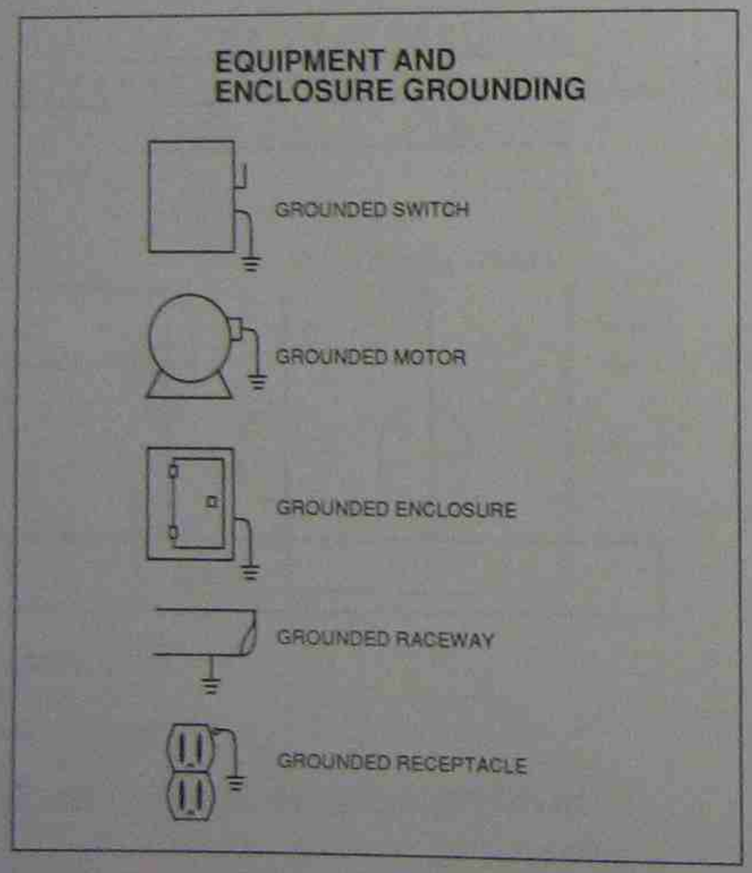


Fig. 13–1 Equipment and enclosure grounding.

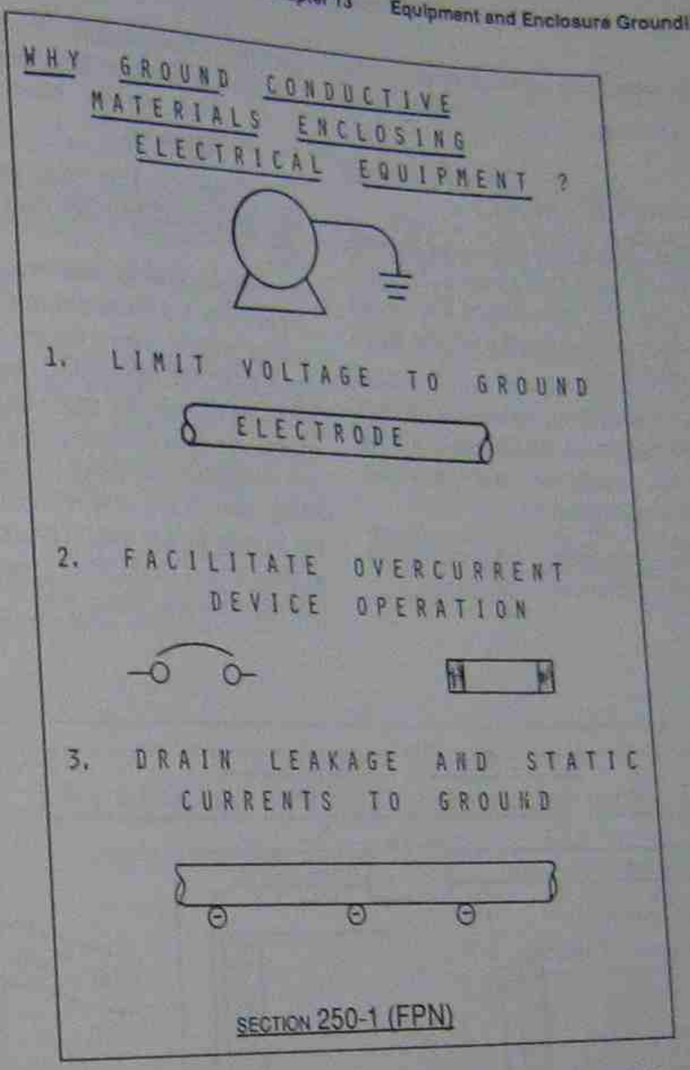


Fig. 13–2 Reasons for grounding conductive materials enclosing electrical equipment.

Electrical equipment enclosures are grounded to

- limit the voltage to ground,
- facilitate sufficient current flow for the operation of the overcurrent protective device,
- drain leakage or static currents to ground.

Part of the reason for grounding has to do with *voltage*. Part of the reason for grounding has to do with *current*. Electrical equipment and enclosure grounding takes into consideration both voltage and current because these two working together pose the greatest danger to individuals and equipment.

Section 300-9, Chapter 3, under *General Provisions* for wiring methods, is another good example of how the Code continually coordinates grounding. *Section 300-9* requires the following metal enclosures to be grounded, according to *Article 250*:

1. Metal raceways
2. Metal boxes
3. Metal cabinets

4. Cable armor
5. Metal fittings

ENCLOSURE GROUNDING

Part D of *Article 250* (Enclosure Grounding) consists of only two sections and each section contains only one sentence. But the two sentences cover all enclosures for the entire electrical installation.

Quote – "Section 250-32, Service Raceways and Enclosures. Metal enclosures for service conductors and equipment shall be grounded."*

Comment: This section takes care of all metal enclosures pertaining to the service.

Quote – "Section 250-33, Other Conductor Enclosures. Metal enclosures for other than service conductors shall be grounded."*

Comment: This takes care of all metal enclosures used for other than service conductors.

Section 250-33 lists two exceptions. Exception No. 1 is illustrated in figure 13–3. This applies mainly where the metal enclosure is used more for mechanical protection of the cable. As an example, apply this exception to a change of wiring methods. An existing installation of nonmetallic sheathed cable (Romex) is being changed to a type of metal raceway wiring. In order for this installation to be made with an ungrounded metal wiring method, there are four requirements. These are:

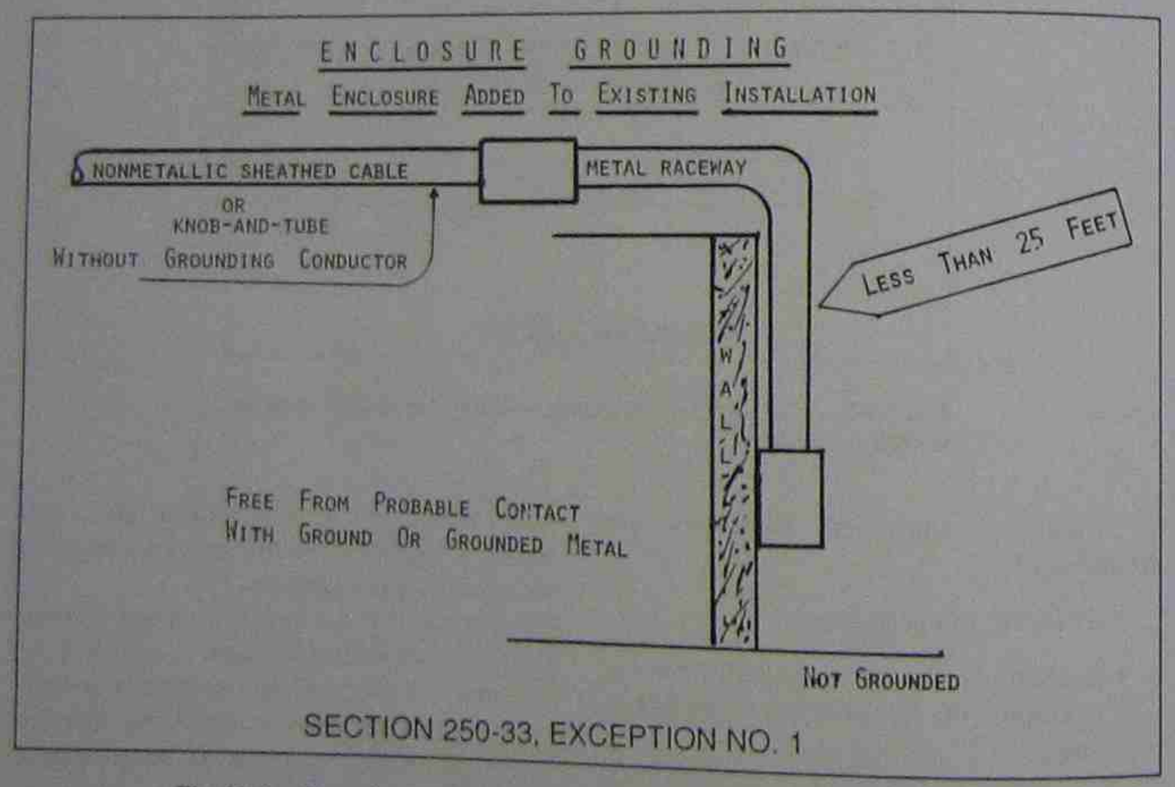


Fig. 13–3 Exception No. 1 to the requirement for metal enclosure grounding.

* Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright ©, 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

1. It must be an addition to an existing installation of knob and tube or nonmetallic sheathed cable.
2. It must be less than 25 feet long.
3. It must be free from probable contact with any grounded surface, such as metal lath.
4. It must be guarded against contact by persons.

Figure 13–4 illustrates Exception No. 2, where a metal enclosure is used to protect cable assemblies. Such cable assemblies would include nonmetallic sheathed cable, service-entrance cable, underground feeder, and branch circuit cable.

Example: The protection illustrated is the same protection required by *Section 336-10(b)* for nonmetallic sheathed cable. It requires the cable to be protected a minimum of 6 inches above the floor.

EQUIPMENT GROUNDING

Here the Code is talking about the electrical equipment used in the workplace or in the home. New electrical equipment is being designed every day to make an individual's job easier, to help that individual do the job faster or better. The equipment must be made safe. One part of safety is the effective grounding of electrical equipment no matter how small or how large the equipment.

There are many sections of the Code that interlock with *Article 250*. Figure 13–5 illustrates some of these interlocking sections. For example:

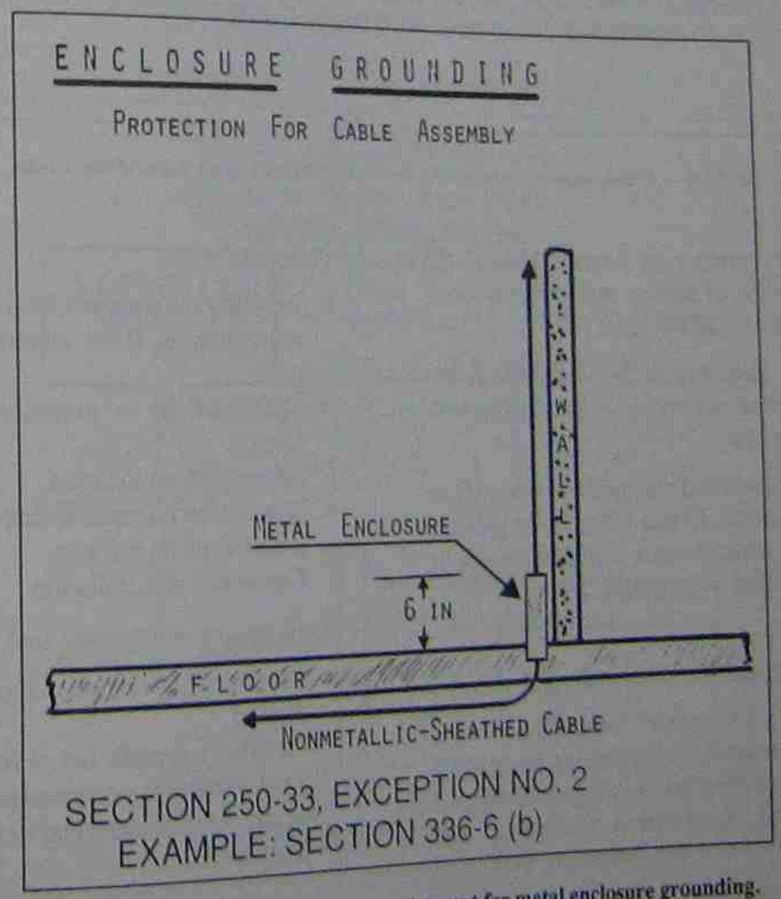


Fig. 13–4 Exception No. 2 to the requirement for metal enclosure grounding.

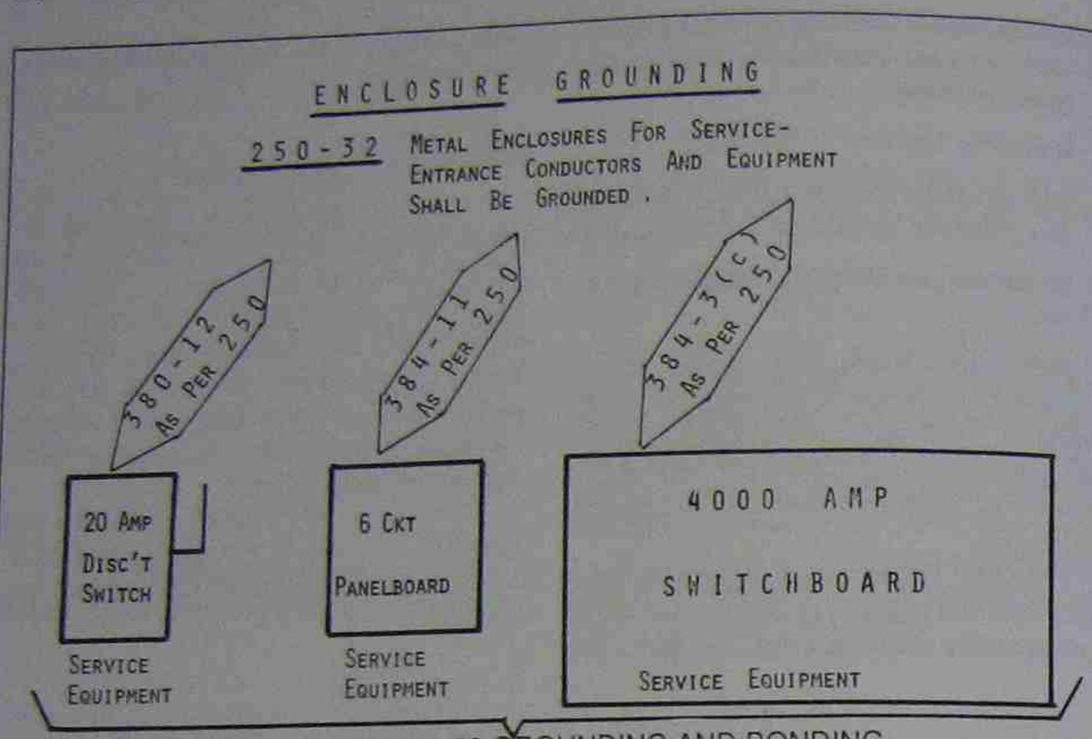


Fig. 13–5 Metal enclosure grounding is coordinated with other parts of the Code.

1. Under *Services* in *Section 230-63*, the grounding of service equipment is interlocked with *Article 250*.
2. Under *Switches* in *Section 380-12*, the grounding of switches is interlocked with *Article 250*.
3. Under *Switchboards and Panelboards* in *Sections 384-11* and *384-3(c)*, the grounding of switchboards and panelboards is interlocked with *Article 250*.

Part E. Equipment Grounding

Part E, Equipment Grounding of *Article 250* sets down the regulations for grounding exposed noncurrent-carrying metal parts of electrical and nonelectrical equipment. The following is a brief but interesting outline of Part E.

1. Fixed equipment
   a. Applies to all exposed noncurrent-carrying parts of fixed electrical equipment
   b. Connected by a permanent wiring method
   c. Information on location
   d. Information on environment
   e. Information on voltage
   f. Conditions of installation
2. Fixed equipment (specific list)
   a. Connected by a permanent wiring method
   b. Identifies a specific list of fixed equipment so there is no mistaking the particular piece of electrical equipment to be grounded
3. Nonelectrical equipment—Lists specific nonelectrical equipment that is required to have its noncurrent-carrying metal parts grounded
4. Equipment connected by plug and cord
   a. Hazardous locations
   b. Over 150 volts to ground
   c. In residential occupancies
   d. In other than residential occupancies

Section 250-42 requires those exposed noncurrent-carrying metal parts of fixed electrical equipment likely to become energized to be grounded under the conditions listed. The listed conditions cover location, environment, and operating voltage.

Guarding and Isolating Electrical Equipment

The exceptions in Part E of *Article 250* permitting equipment to be installed without being grounded are taking into consideration one or more of the following points:

1. Specific piece of equipment
2. Double insulation
3. Guarded equipment
4. Isolated equipment

Equipment Required to Be Grounded

Figure 13–6 illustrates the 8-foot vertical and 5-foot horizontal distances electrical equipment must be from ground or a grounded surface before it can be installed ungrounded. When the equipment is installed with less than these distances to ground, the equipment shall be grounded.

When electrical equipment is located in a wet or damp location, it shall be grounded. Figure 13–7 shows an example of this, where an outdoor air conditioning unit is installed at

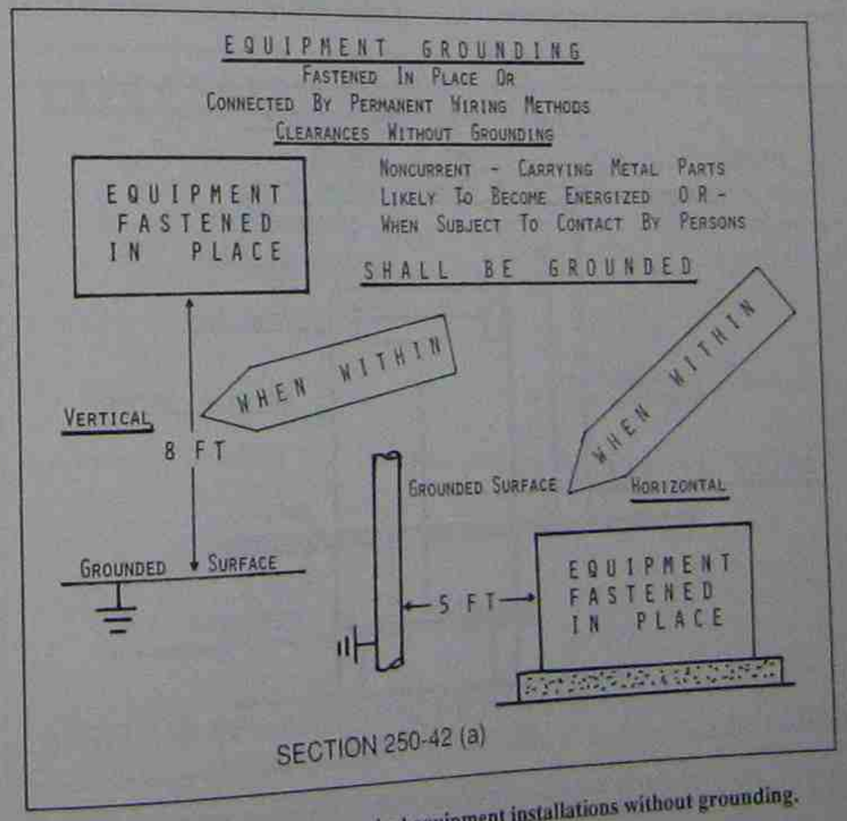


Fig. 13–6 Clearances for electrical equipment installations without grounding.

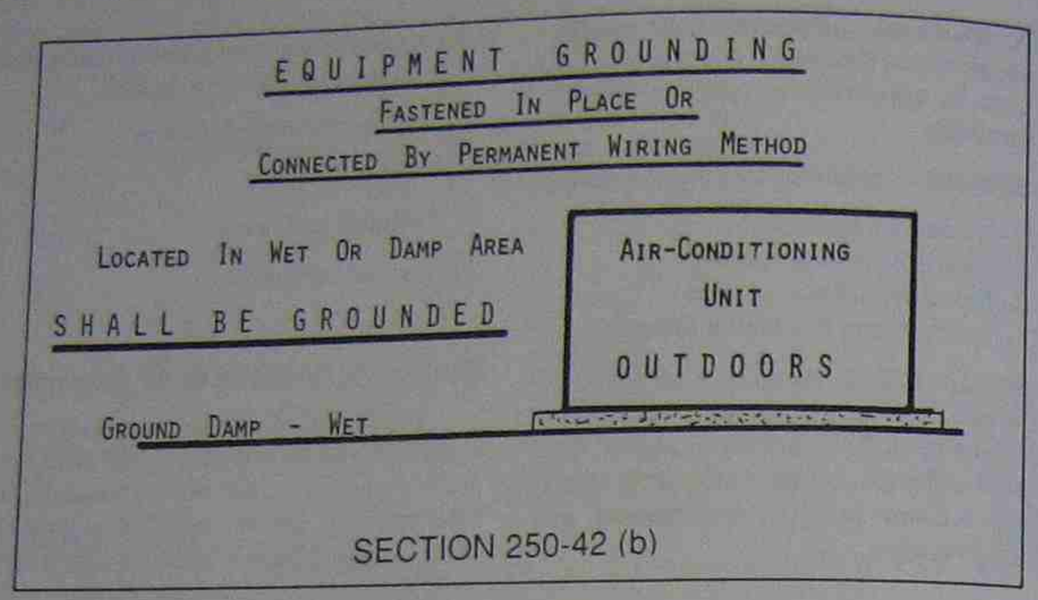


Fig. 13–7 Electrical equipment installed in a damp or wet location shall be grounded.

ground level. Anyone could walk up and touch it while standing on earth that may or may not be damp or wet.

Figure 13–8 illustrates *Section 250-42(c)*, where an enclosure for electrical equipment is in contact with metal that could possibly become energized through a fault in the enclosure. In this case, it shall be grounded. For grounding in hazardous locations or health care facilities, *Article 250* refers to *Articles 500* and *517*.

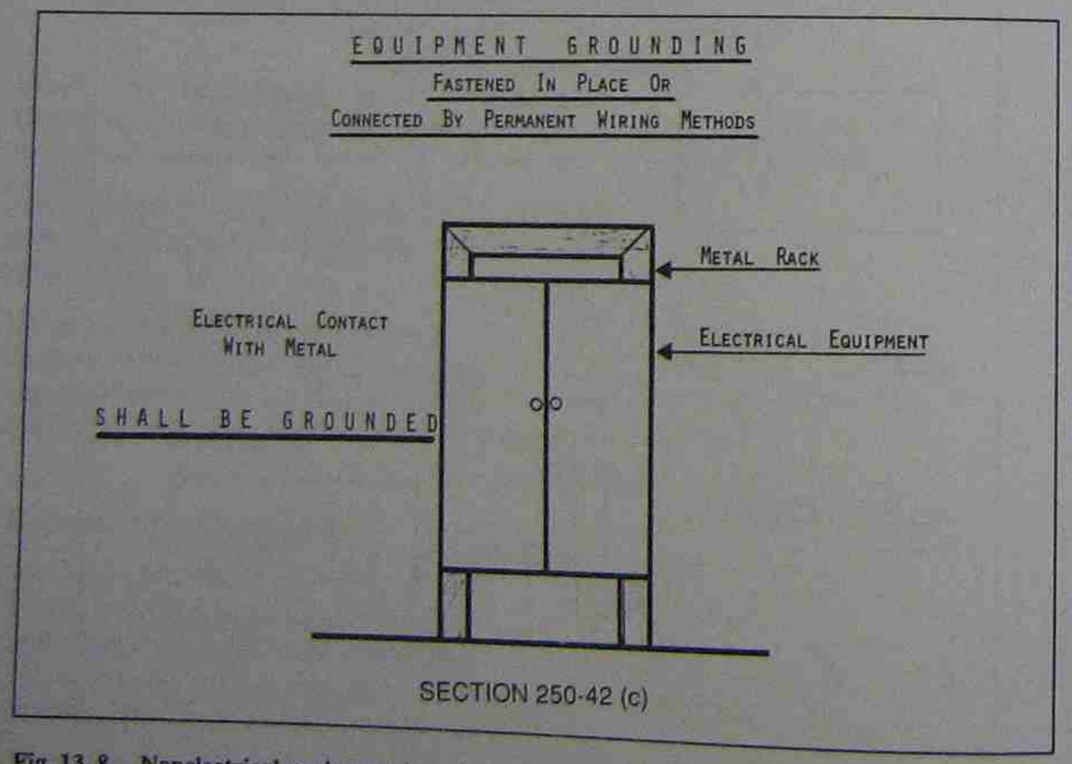


Fig. 13–8 Nonelectrical equipment in metal contact with electrical equipment shall be grounded.

Equipment Connected by Permanent Wiring

When the equipment is supplied by any of the metallic wiring methods listed in Chapter 3, *Wiring Methods and Materials*, it shall be grounded. Such conductor-enclosure wiring methods include:

- Rigid metal conduit
- Intermediate metal conduit
- Electrical metallic tubing
- Flexible metal conduit
- Flexible metallic tubing
- Surface metal raceway
- Metal wireway
- Metal underfloor duct
- Metal bus duct
- Any wiring method with a metal covering

When the equipment is supplied by any of the metal-covered cable assemblies listed in Chapter 3 of the Code, the metal covering shall be grounded. Such cable assemblies include:

1. Type AC armored cable
2. Type MC metal-clad cable
3. Type MI mineral-insulated cable
4. Any other cable assembly with a metal covering

Section 250-42(f) gives a blanket requirement for grounding all equipment operating over 150 volts to ground, with four exceptions. Figure 13–9 illustrates *Section 250-42(f)*, Exception No. 3, where the equipment is mounted more than 8 feet above ground level.

Figure 13–10 illustrates *Section 250-42(f)*, Exception No. 4 as it applies to listed office equipment such as computers. Note the section heading: "Over 150 Volts to Ground." This

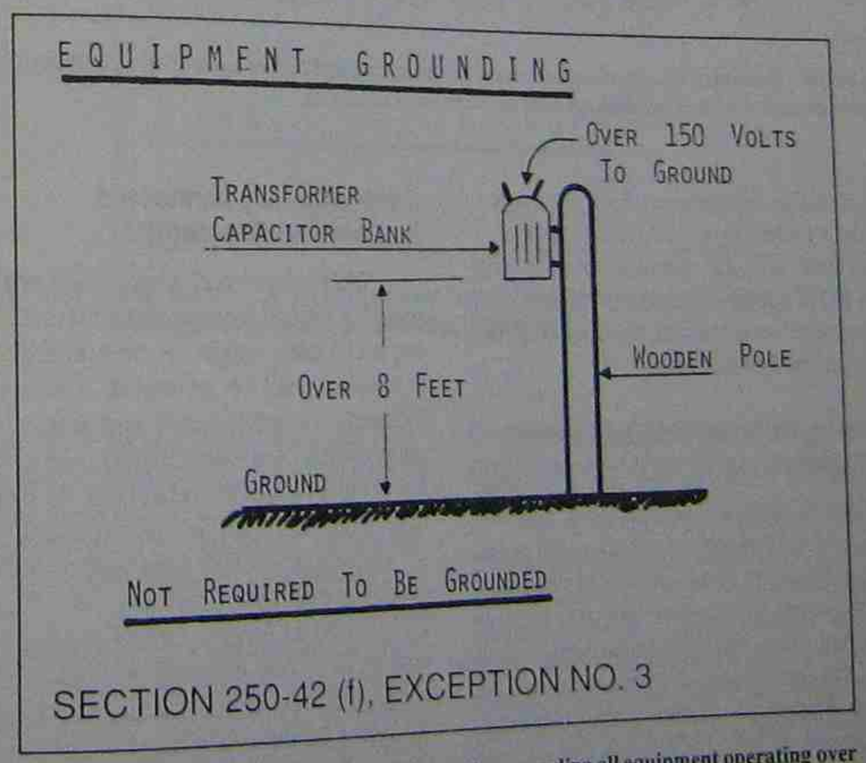


Fig. 13–9 Exception No. 3 to the requirement for grounding all equipment operating over 150 volts to ground.

EQUIPMENT GROUNDING

OFFICE EQUIPMENT

PERMITTED TO BE UNGROUNDED WHEN

1 - OVER 150 VOLTS TO GROUND
2 - DOUBLY INSULATED
3 - LISTED EQUIPMENT
4 - DISTINCTIVELY MARKED

SECTION 250-42 (f), EXCEPTION NO. 4

Fig. 13–10 Exception No. 4 to the requirement for grounding listed office equipment operating over 150 volts to ground. Courtesy International Business Machines Corporation.

means that this requirement does not apply to equipment operating at 120 volts to ground.

Section 250-43 contains a list (figure 13–11) of specific equipment that is fixed in place and shall be grounded, *regardless of voltage*. There are few exceptions.

Grounding Nonelectrical Equipment

There are situations that can arise when some piece of electrical equipment is mounted on nonelectrical equipment, which could possibly cause the entire metal parts of the nonelectrical equipment to become energized. In these installations, the noncurrent-carrying metal parts of the nonelectrical equipment shall be grounded. Figure 13–12 shows the nonelectrical equipment, as listed in *Section 250-44*, that shall be grounded.

Cord- and Plug-connected Equipment—Residential

Where cord- and plug-connected equipment is used and the exposed noncurrent-carrying metal parts might become energized, the equipment shall be grounded. There are two locations in which the cord- and plug-connected equipment is used: one is in the home or residential occupancy and the other is in the workplace or in other than a residential occupancy.

Damp or wet locations tend to set up hazardous conditions. Therefore, the Fine Print Note (FPN) to *Section 250-45* explains the intent of the Code concerning cord- and plug-connected tools or appliances. The Code does not intend for these tools and/or appliances to be used in damp or wet locations, whether it is a residential or other location.

EQUIPMENT GROUNDING

FASTENED IN PLACE OR
CONNECTED BY PERMANENT WIRING METHOD

SPECIFICS

SWITCHBOARD FRAMES AND STRUCTURES

ORGANS

MOTOR FRAMES

ENCLOSURES FOR MOTOR CONTROLLERS

ELEVATORS AND CRANES

GARAGES, THEATERS, AND MOTION PICTURE STUDIOS

ELECTRIC SIGNS

MOTION PICTURE PROJECTION EQUIPMENT

CLASS 1, CLASS 2, AND CLASS 3 CIRCUITS

LIGHTING FIXTURES

SHALL BE GROUNDED

SECTION 250-43

Fig. 13–11 A list of equipment fastened in place or connected by permanent wiring that is required to be grounded.

Figure 13–13 is a list of cord- and plug-connected equipment that shall be grounded, as required by *Section 250-45(c)*, when this equipment is located in a *residential occupancy*. Figure 13–14 illustrates the exception to *Section 250-45(c)*, which allows the use of double insulation on listed tools and appliances. When such double insulation is used, it shall be distinctively marked. This exception is also repeated in *Section 422-8(d)* for kitchen waste disposers, trash compactors, and dishwashers.

Cord- and Plug-connected Equipment—Other Than Residential

Figure 13–15 is a list of items taken from *Section 250-45(d)* that shall be grounded when they are located *in other than residential occupancies*. The list repeats almost everything listed on the residential list (figure 13–13) plus several more items. There are two exceptions here, one recognizing the double-insulated tool or appliance and one the use of an isolation

EQUIPMENT GROUNDING

NONELECTRIC EQUIPMENT

CRANES

ELEVATOR CARS

ELECTRIC ELEVATORS

METAL PARTITIONS

MOBILE HOMES AND RECREATIONAL VEHICLES

SHALL BE GROUNDED

SECTION 250-44

Fig. 13–12 Nonelectrical equipment that shall be grounded.

EQUIPMENT GROUNDING

CORD AND PLUG CONNECTED

HAZARDOUS LOCATIONS

OVER 150 VOLTS TO GROUND

IN RESIDENTIAL OCCUPANCIES

- REFRIGETORS
- FREEZERS
- AIR CONDITIONERS
- CLOTHES – WASHING
- CLOTHES – DRYING
- DISHWASHING MACHINES
- SUMP PUMPS
- ELECTRICAL AQUARIUM EQUIPMENT
- HAND-HELD, MOTOR-OPERATED TOOLS
- MOTOR-OPERATED APPLIANCES
  - HEDGE CLIPPERS
  - LAWN MOWERS
  - SNOW BLOWERS
  - WET SCRUBBERS
- PORTABLE HANDLAMPS

SHALL BE GROUNDED

SECTION 250-45 (c)

Fig. 13–13 Cord- and plug-connected equipment that shall be grounded when located in a residential area.

DOUBLE INSULATION

INSTEAD OF GROUNDING

PORTABLE TOOLS - APPLIANCES

SECTION 250-45 AND 422-8

(EXCEPTIONS)

Fig. 13–14 Exceptions that allow the use of double insulation on listed tools and appliances. Courtesy Black & Decker.

EQUIPMENT GROUNDING

CORD AND PLUG CONNECTED

IN OTHER THAN RESIDENTIAL OCCUPANCIES

- REFRIGETORS
- FREEZERS
- AIR CONDITIONERS
- CLOTHES – WASHING
- CLOTHES – DRYING
- DISHWASHING MACHINES
- ELECTRONIC COMPUTER DATA PROCESSING EQUIPMENT
- SUMP PUMPS
- ELECTRICAL AQUARIUM EQUIPMENT
- HAND-HELD, MOTOR-OPERATED TOOLS
- MOTOR-OPERATED APPLIANCES
  - HEDGE CLIPPERS
  - LAWN MOWERS
  - SNOW BLOWERS
  - WET SCRUBBERS
- CORD- AND PLUG-CONNECTED APPLIANCES
  - DAMP LOCATIONS
  - WET LOCATIONS
  - PERSONS STANDING ON GROUND
  - PERSONS STANDING ON METAL FLOOR
  - PERSON INSIDE METAL TANK OR BOILER
- TOOLS LIKELY TO BE USED
  - WET LOCATIONS
  - CONDUCTIVE LOCATIONS
- PORTABLE HANDLAMPS

SHALL BE GROUNDED

SECTION 250-45 (d)

Fig. 13–15 Cord- and plug-connected equipment that shall be grounded when located in other than residential occupancies.

transformer, as illustrated in figure 13–16. An example of this exception would be the use of an isolation transformer for low-voltage lighting used for temporary lighting inside a large metal tank.

CAUTION: The list given for residential occupancies and for other than residential occupancies is not an all-inclusive list of everything that shall be grounded.

Example: Section 310-6, illustrated in figure 13–17, requires the metal shield of conductors operating at over 2000 volts to be grounded.

METHODS OF GROUNDING ENCLOSURES AND EQUIPMENT

Section 250-57 lists the ways that cord- and plug-connected equipment is permitted to be grounded. These are:

1. By the use of metal enclosures and/or metal raceways, or the use of metal covering of some cable assemblies and fittings listed for the purpose. The raceway or cable must contain the circuit conductors serving the equipment.

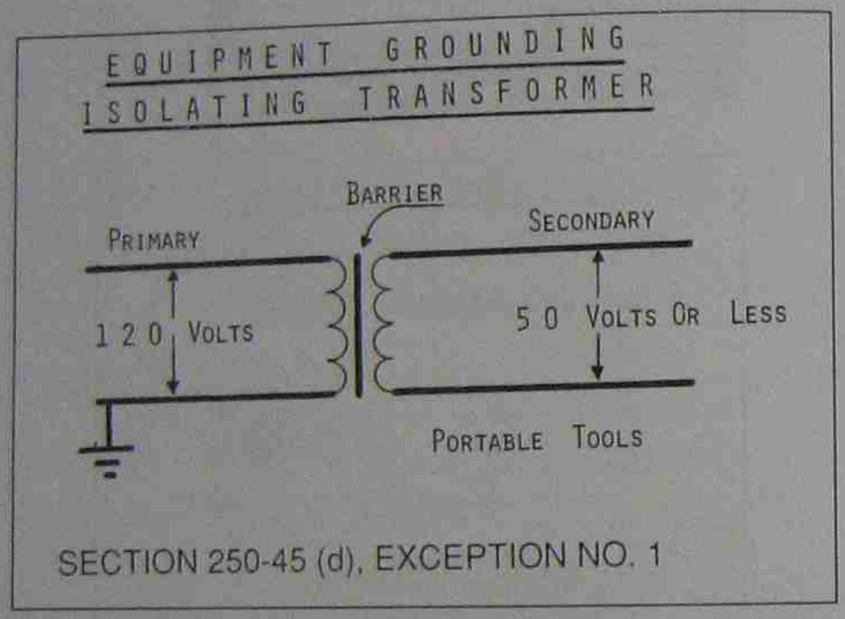


Fig. 13–16 An isolation transformer is permitted with an ungrounded secondary.

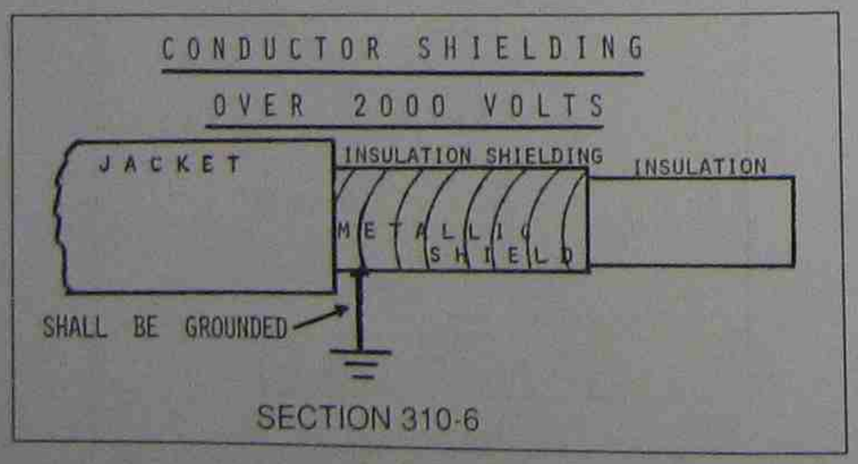


Fig. 13–17 Requirement for grounding metal conductor shielding operating over 2000 volts.

2. By the use of an equipment grounding conductor contained within the same raceway, cable, or cord.
3. *Section 250-59(c)* permits grounding cord- and plug-connected equipment by the following means:
   a. Separate flexible wire
   b. Separate flexible strap
   c. Wire or strap—permitted to be insulated or bare
   d. Wire or strap—shall be protected, as well as is practical, against physical damage.

Grounding Panelboards

Section 384-27 (figure 13–18) requires a ground bar for the neutral conductor connections and an equipment grounding bar for the equipment grounding conductor connections in distribution panels where nonmetallic raceway is used. There are several points covered by *Section 384-27* for an installation using nonmetallic raceway, when wire is used for equipment grounding conductors. These are:

1. An approved terminal bar shall be used.
2. The terminal bar shall be secured inside the cabinet.
3. The terminal bar shall be specifically for the connection of equipment grounding conductors.
4. The equipment grounding conductors can be for feeders or for branch circuits.
5. The equipment grounding terminal bar shall be bonded to the cabinet or panelboard frame.
6. For a separately derived system, the equipment grounding terminal bar shall be located at the first system disconnecting means or overcurrent device.

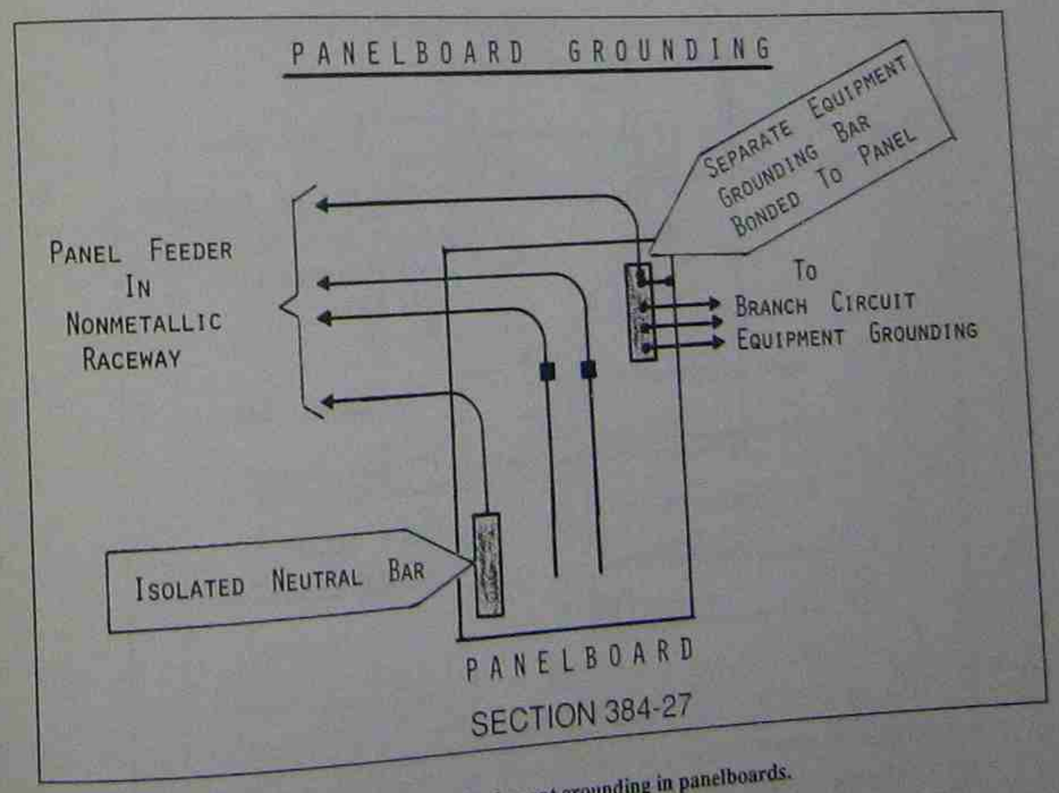


Fig. 13–18 Equipment grounding in panelboards.

7. The equipment grounding bar shall not be connected to the neutral bar in any panel other than the service equipment.
8. When two buildings are served from one service, the equipment grounding bar and the neutral bar are permitted to be connected together at the main disconnecting means at the second building.

Figure 13–19 illustrates the installation of a separate ground bar in a cabinet for the neutrals and a separate ground bar for the equipment grounding conductors.

Reason: By having two separate bars—one for the neutral and one for the equipment grounding—the current flow (the electron flow) is controlled, as illustrated in figure 13–20. There is only one path for the current to flow on, even though the grounded conductor (the neutral) does furnish the return path for the current flow.

Figure 13–21 illustrates a series circuit that ends in many parallel paths. When the neutral conductor is bonded to panels other than the service equipment, many paths are created and the electrons will take each and every path offered. There no longer is control over the electron flow (figure 13–22). The electrons now have a multitude of paths for return to the source, paths for circulating ground currents are established, and this is just another way to install "dirty, noisy" electricity.

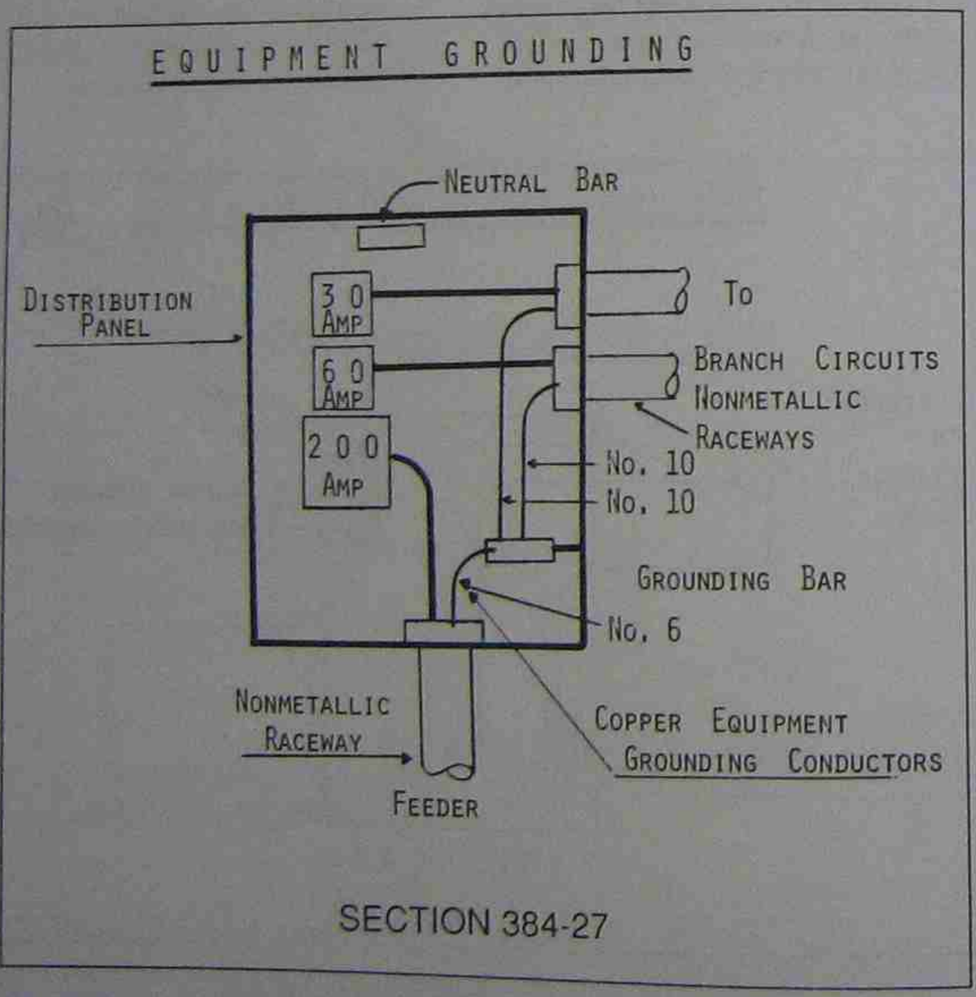


Fig. 13–19 Use of a separate neutral bar and a separate equipment grounding bar in panels.

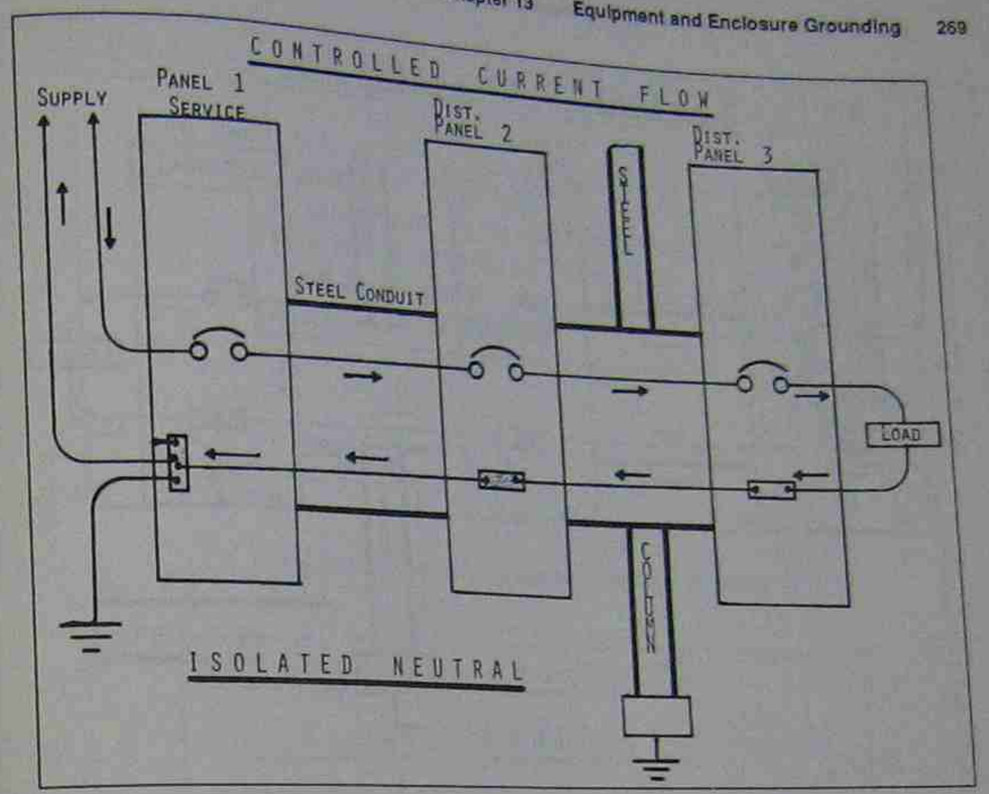


Fig. 13–20 Controlled current flow when the neutral bar is connected to the service enclosure only.

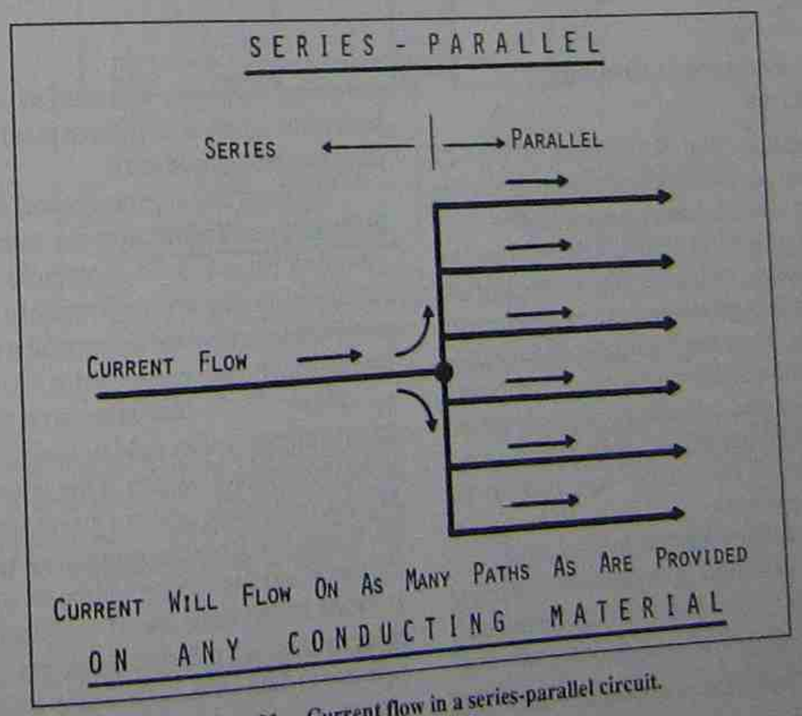
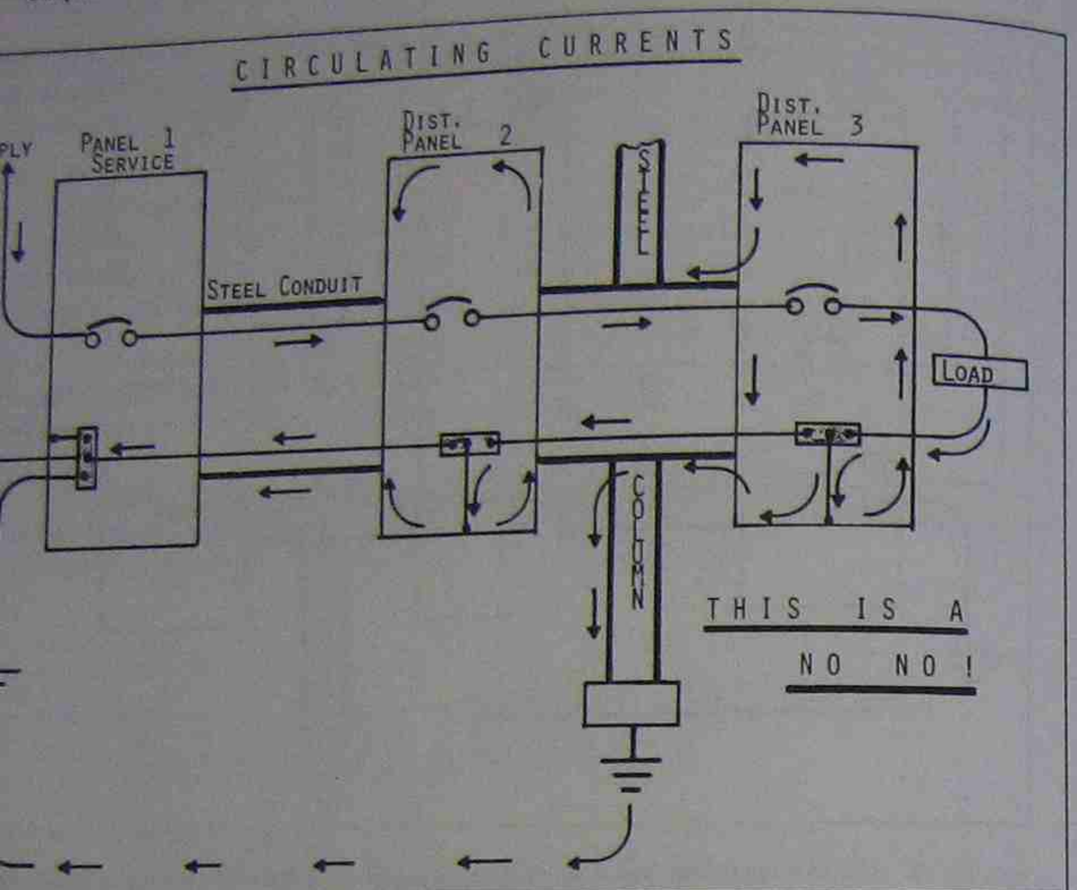


Fig. 13–21 Current flow in a series-parallel circuit.



22 Uncontrolled current flow when neutral is bonded to each enclosure. Many paths for circulating are created.

ed Equipment Grounding tacles

ception No. 1 of *Section 384-27* of an isolated equipment grounding tor. The isolated equipment grounding tor is used in conjunction with an iso- ounding receptacle (figure 13–23). Iso- uipment grounding receptacles are used tals. They are also used in conjunction mputers and data processing equipment. ie isolated grounding receptacle is used, ated equipment grounding conductor is ed to be run all the way back to the ng electrode conductor connection at ice, as illustrated in figure 13–24.

ere are really two equipment grounding ors involved here. One is the isolated, d equipment grounding conductor con- o the green terminal on the isolated grounding receptacle and carried all the way back to the supply with a green insulated equipment grounding conductor.

The metal box (the enclosure) housing the isolated grounding receptacle must also be grounded, but not to the receptacle. When the receptacle is fed with effectively grounded metal conduit, the conduit becomes the second equipment grounding conductor.

Figure 13–25 illustrates how an isolated grounding receptacle could be installed, when a separately derived system is the source of supply. An insulated equipment grounding conductor is installed from the grounding terminal of the receptacle back to the source of supply. It is installed in the same metal raceway with the feeder and branch circuit conductors. The metal raceway is then used as the equipment grounding conductor for things other than the isolated

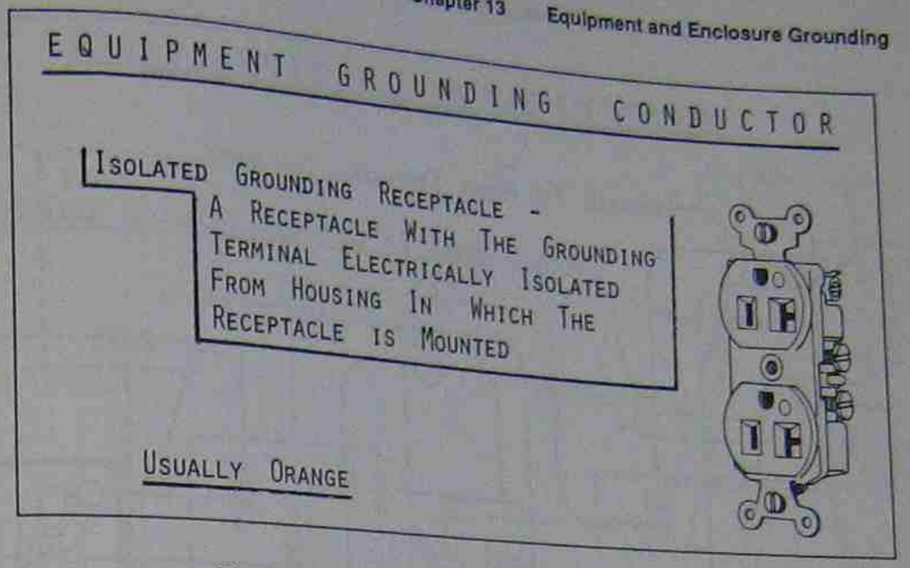


Fig. 13–23 Definition of *isolated grounding receptacle.*

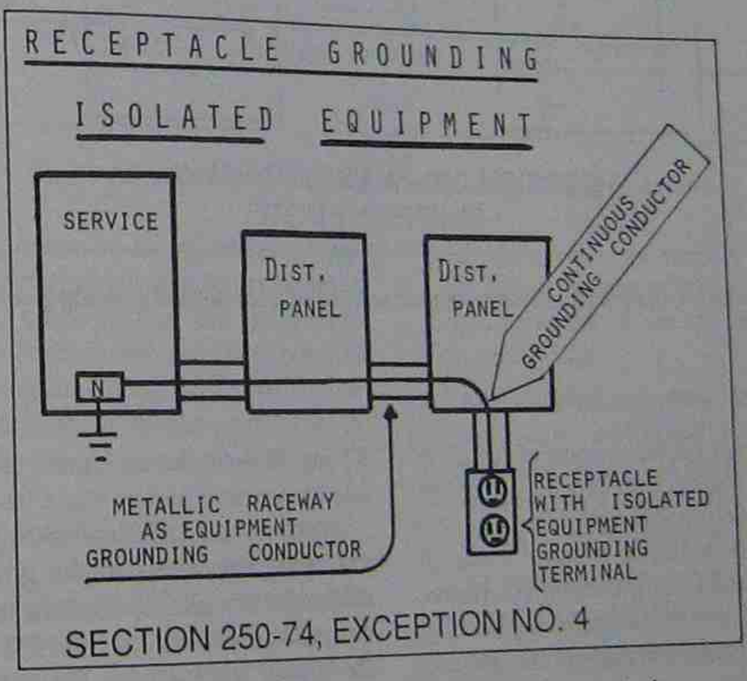
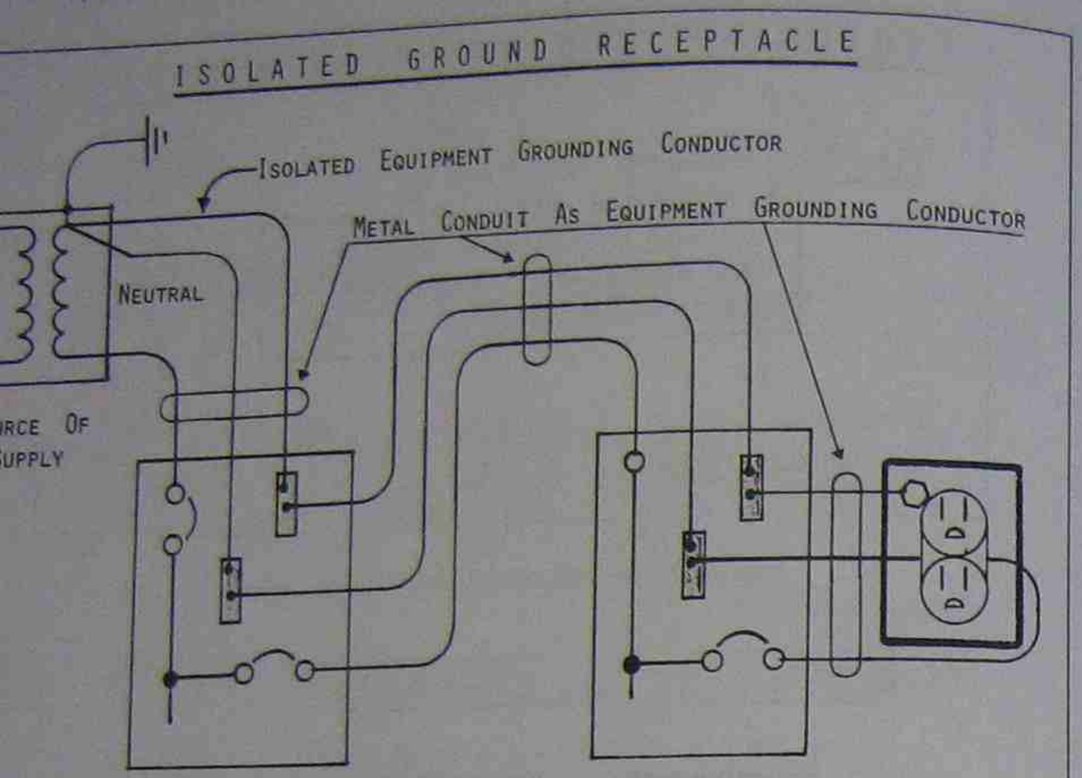


Fig. 13–24 Installation of an isolated grounding receptacle.

grounded receptacle. In this particular illustration (the source of supply being a separately derived system) there is more than one way that the source of supply could be installed. For example:

1. It can be connected through a ground bar back to the point of connection of the grounding electrode conductor.
2. It can be carried directly back to the point of connection of the equipment grounding conductor.
3. It can be connected to the neutral bar at the first disconnecting means or overcurrent protective device.

Reason: The isolated grounding receptacle and the isolated equipment grounding



–25 Insulated equipment grounding conductor installed from isolated grounding receptacle back to of supply.

ctor help to get rid of some of that dirty city that causes problems for computers ner microelectronic equipment.

When an installation is made using all tallic conduit, two grounding conductors required, one for the isolated grounding cle and one for other equipment ground-

Grounding

hen a tower is connected by any electri- ductors, as a TV tower might be con- at a residence, the equipment grounding tor shall be run to the tower and con- to the tower, as shown in figure 13–26. ure illustrates a fault that could take place the tower and the aerial lead back to the TV set. Without the equipment grounding conductor, a serious hazard could be created.

The tower is permitted to be grounded to a grounding electrode, but the grounding electrode does not take the place of the equipment grounding conductor. *Section 250-51* prohibits the use of the earth as the sole equipment grounding conductor.

Computer Grounding

As stated in *Section 90-1(c)*, the Code is not intended as a design specification manual. The purpose of the Code is to protect people and property from hazards arising from the use of electricity *(Section 90-1(a))*. However, to accomplish the purpose of the Code and have an effectively grounded system, Code regulations

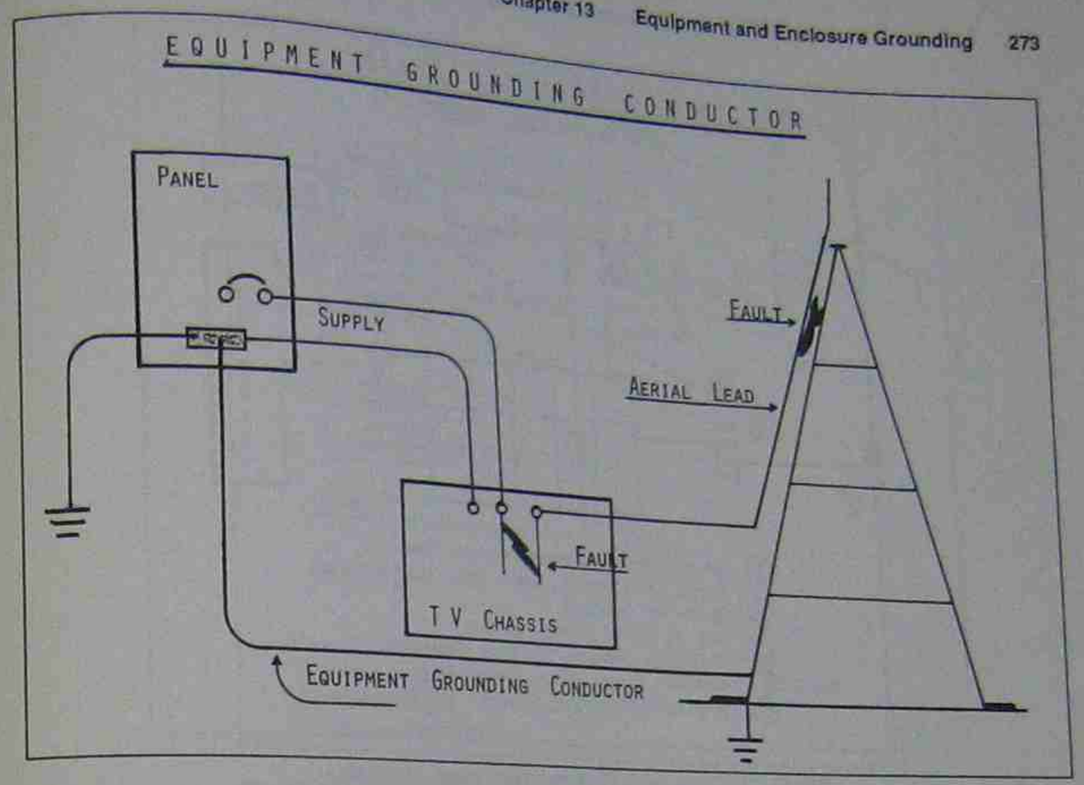


Fig. 13–26 Tower grounding with an equipment grounding conductor.

for grounding must be incorporated into the design of any electrical installation or computer system. The Code gives the minimum requirements. There is nothing in the Code that prohibits making an installation better. In the case of computers, the installation almost has to be better than the minimum Code requirements.

A book in itself could be written on computer grounding, and this text is not intended to include all the information on the subject. The relationship between computer grounding and the requirements of the *National Electrical Code* will be covered here, especially some of the things the Code requires and some of the things the Code permits. Successful computer grounding can be accomplished and can be compatible with the Code regulations. For example, the Code requires the following:

1. All grounding shall be installed in accordance with *Article 250*, including:
   a. Grounding electrode
   b. Grounded conductor
   c. Main bonding jumpers
   d. Grounding conductor
   e. Equipment and enclosure bonding and grounding
2. All noncurrent-carrying metal parts of equipment and enclosures shall be grounded so there is no potential difference between a piece of equipment and ground (*Section 250-33*).
3. All grounding electrodes shall be bonded together (*Section 250-81*).
4. Where a separately derived system is used, it shall comply with separately derived system installations.

The Code permits the following:

1. An isolated grounding system is permitted (*Section 250-74*, Exception No. 4 and *Section 384-27*, Exception No. 1).
2. Equipment protected by a double insulation or an equivalent shall not be required to be grounded (*Section 250-42*, Exception No. 4).

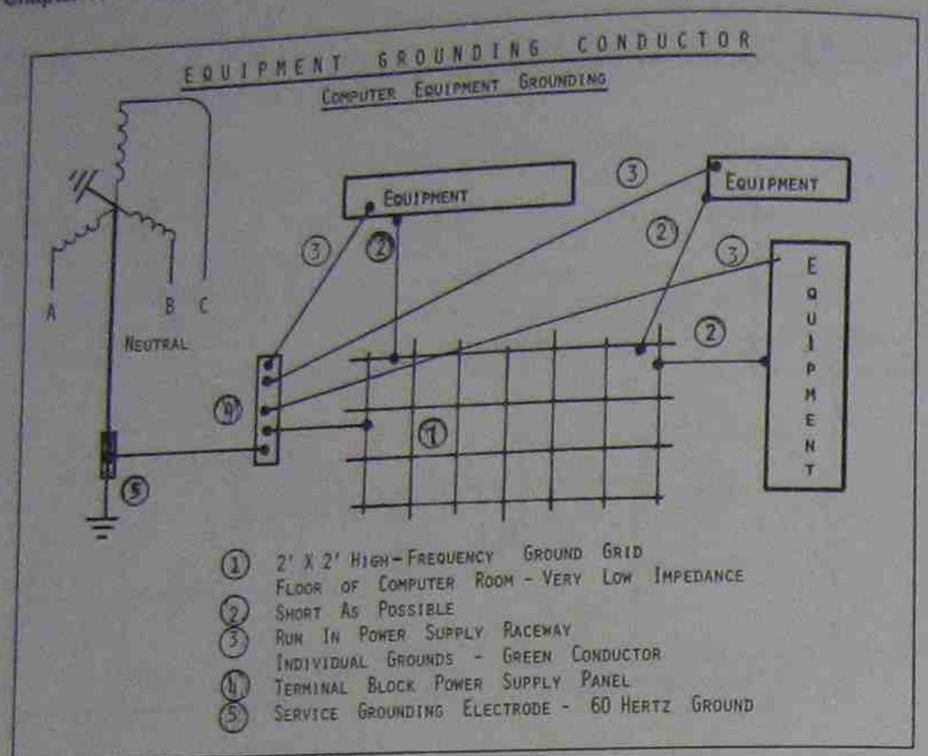


Fig. 13–27 One method of computer room grounding.

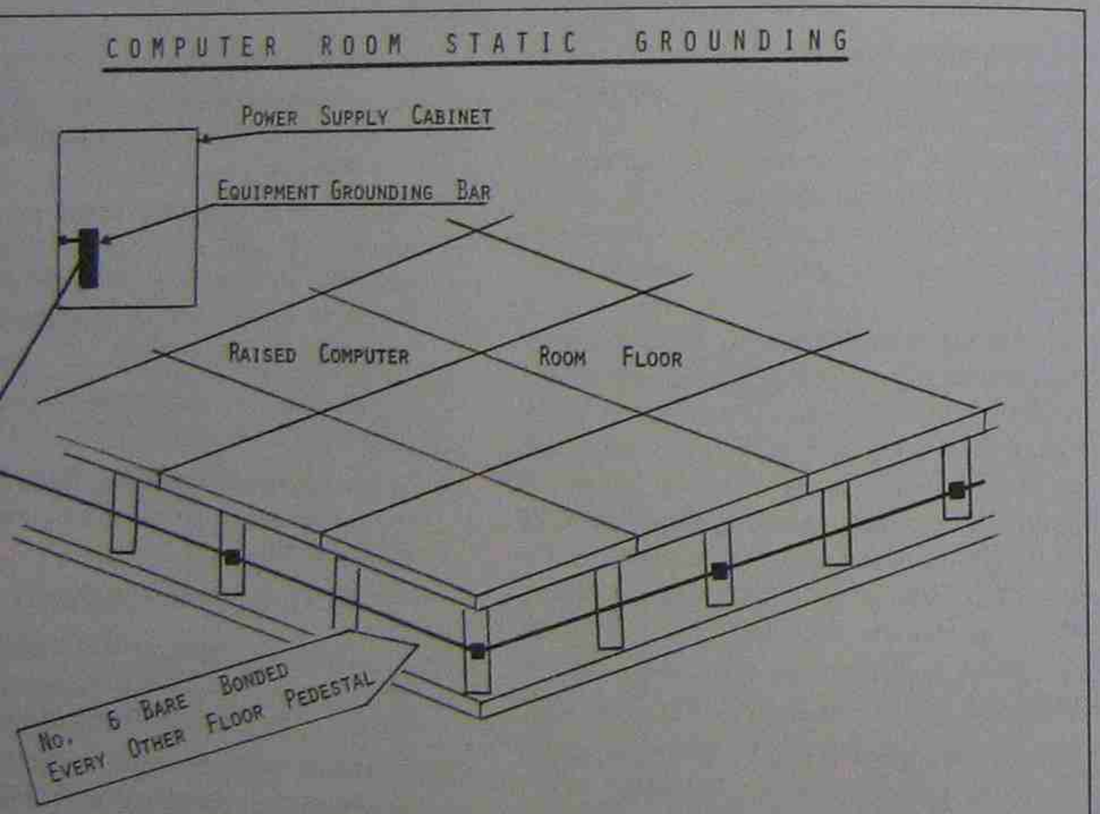


Fig. 13–28 One method of grounding a computer room floor.

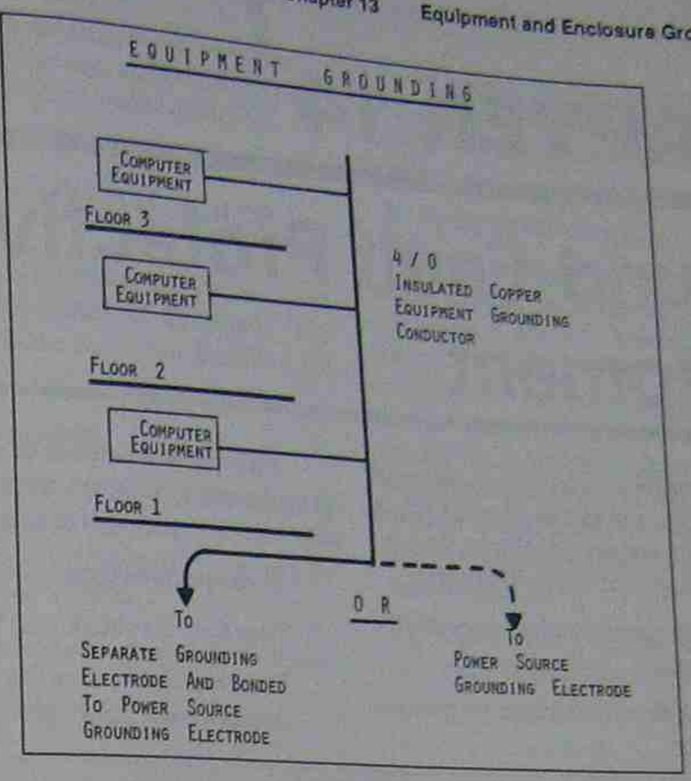


Fig. 13–29 A separate No. 4/0 copper conductor riser used for computer grounding.

3. When the power source and the computer source are common, a separate grounding electrode is permitted to be established, but it shall be bonded to the service equipment grounding electrode *(Section 250-91(c))*.

4. An entirely separately derived system, dedicated to computer equipment with a separate grounding electrode and equipment grounding, is permitted (*Section 250-26*).

Figure 13–27 illustrates how a computer system could have its own isolated equipment grounding system, common with the power source grounding electrode. All equipment grounding conductors used are insulated copper conductors, run the shortest distance possible. All collect at the special grounding bar in the power distribution panel and all return to the grounding electrode by means of an insulated, unbroken, equipment grounding conductor. Where a computer floor is used and is set on metal floor pedestals, the pedestals are permitted to be bonded and connected to the special ground bar in the power panel (figure 13–28).

Figure 13–29 illustrates the use of a No. 4/0 insulated copper conductor installed as a grounding electrode conductor riser for computer grounding. The riser is used to establish a common grounding electrode for separately derived systems on the various floors. It is connected to a separate grounding electrode or to the power source grounding electrode. When connected to a separate grounding electrode, it is bonded to the power source grounding electrode. Where computer equipment is interconnected on different floors, the same reference point to ground is established on all floors. It is used in place of building steel on one floor and the metal water piping on another floor for a separately derived system.

CHAPTER 14

Ground-Fault Protective Equipment

This chapter focuses on the two pieces of ground-fault equipment required by the Code to protect equipment and personnel from the hazards arising from ground faults. These are:

1. Ground-fault protection device for equipment protection
2. Ground-fault circuit interrupter for personnel protection

Although the purpose of these two pieces of equipment is different, there are three things they have in common. These are:

1. Their operation depends on a ground fault.
2. They open the circuit with the ground fault.
3. There is a certain time frame within which the equipment must open the circuit.

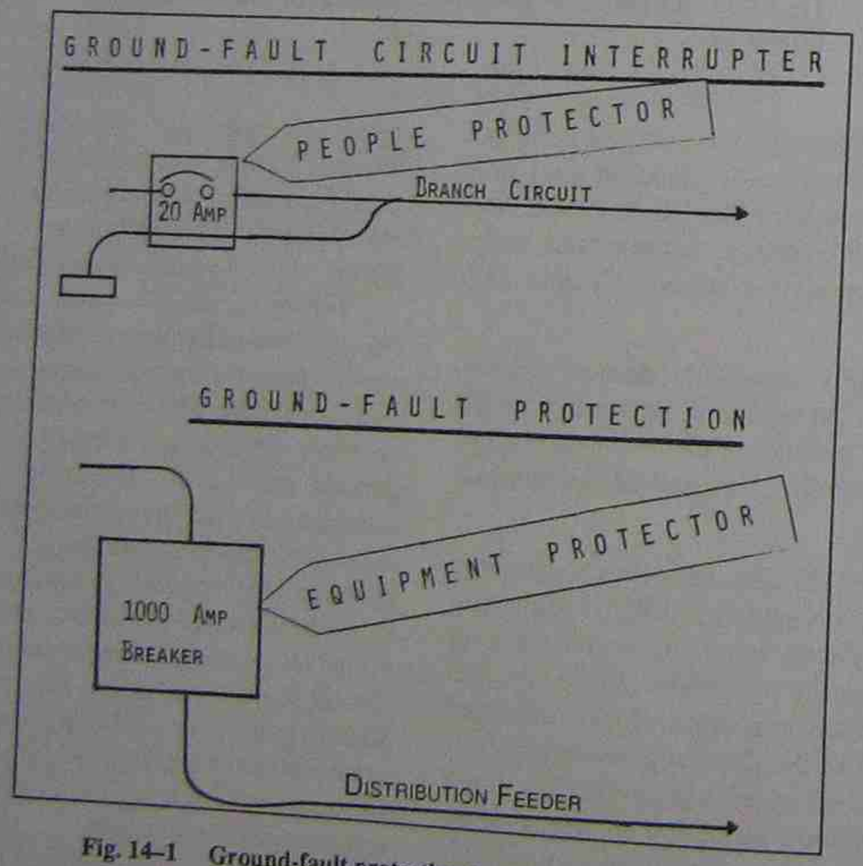


Fig. 14–1 Ground-fault protection for people and equipment

Ground faults are arcing faults; arcing creates heat, heat creates fire, and heat will attack and destroy the conductor insulation.

GROUND-FAULT PROTECTION OF EQUIPMENT

Figure 14–2 illustrates the definition of *Ground-Fault Protection of Equipment*. The following lists some important points in the definition.

1. Protects equipment

Comment: There is no mention of personnel because the fault current trip setting of a ground-fault protector is of such magnitude that it could be fatal to a person.

2. Operates on line-to-ground fault current

Comment: The ground-fault protector gives no phase-to-phase fault protection. That is the responsibility of the overcurrent protective device.

3. Opens the disconnecting means

Comment: There are no ringing bells, there are no flashing lights, there is no warning, but the circuit is opened, whether it is a service, feeder, or branch circuit. The disconnecting means can be a switch or a circuit breaker with proper current and voltage ratings that can be automatically operated. It is hoped that the overcurrent device nearest the ground fault will open the faulted circuit and disconnect only that part of the circuit before the ground-fault protection operates.

4. Operates at a current level less than the circuit overcurrent device is set for

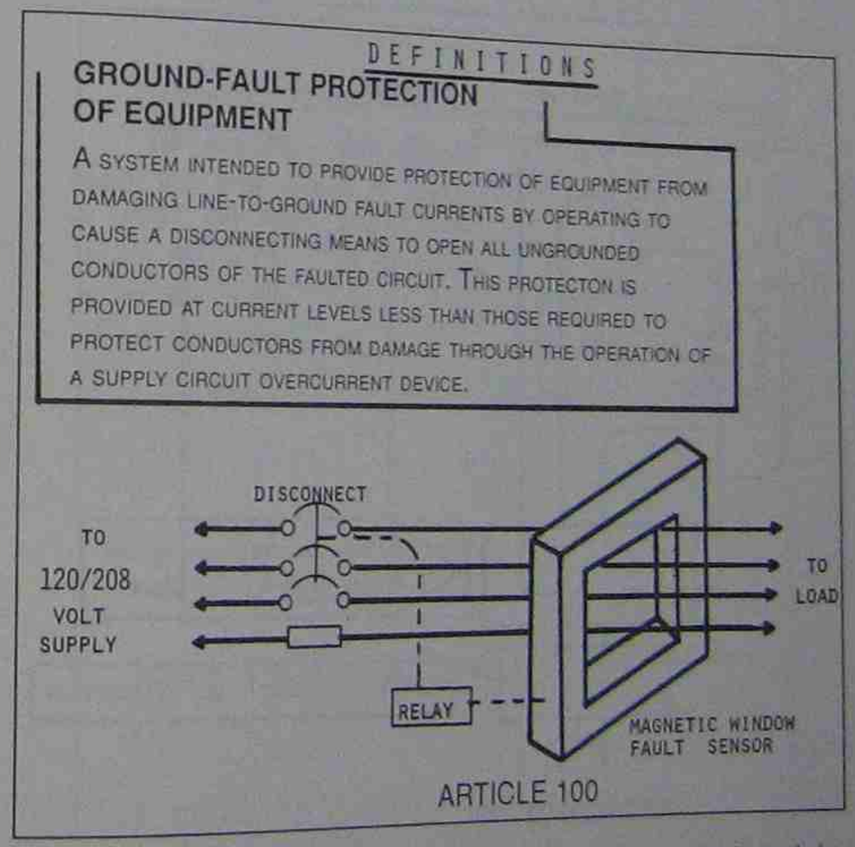


Fig. 14–2 Definition of *ground-fault protection of equipment*. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright ©, 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety.

Comment: A ground fault can draw current and still not trip the circuit overcurrent protective device. For example, a 1200-amp overcurrent device has an 800-amp load working and there is a 200-amp ground fault. The breaker sees the total current needed as 1000 amps and continues to furnish 1000 amps. The overcurrent device does not operate.

GROUND-FAULT PROTECTION EQUIPMENT REQUIRED

Section 230-95 (figure 14–3) sets the basic rules for equipment ground-fault protection. All of the following conditions must be met before ground-fault protection of equipment is required:

1. Solidly grounded
2. Wye connected service
3. More than 150 volts to ground
4. Not exceeding 600 volts between phases
5. Disconnecting means rated for 1000 amps or more
6. All ungrounded conductors opened by service disconnecting means
7. Maximum setting of overcurrent device: 1200 amps
8. Maximum time delay for opening service disconnecting means: 1 second for ground-fault currents 3000 amps or larger
9. Equipment ground-fault protection permitted on distribution feeders
10. Equipment ground-fault protection permitted on disconnecting means rated at less than 1000 amps

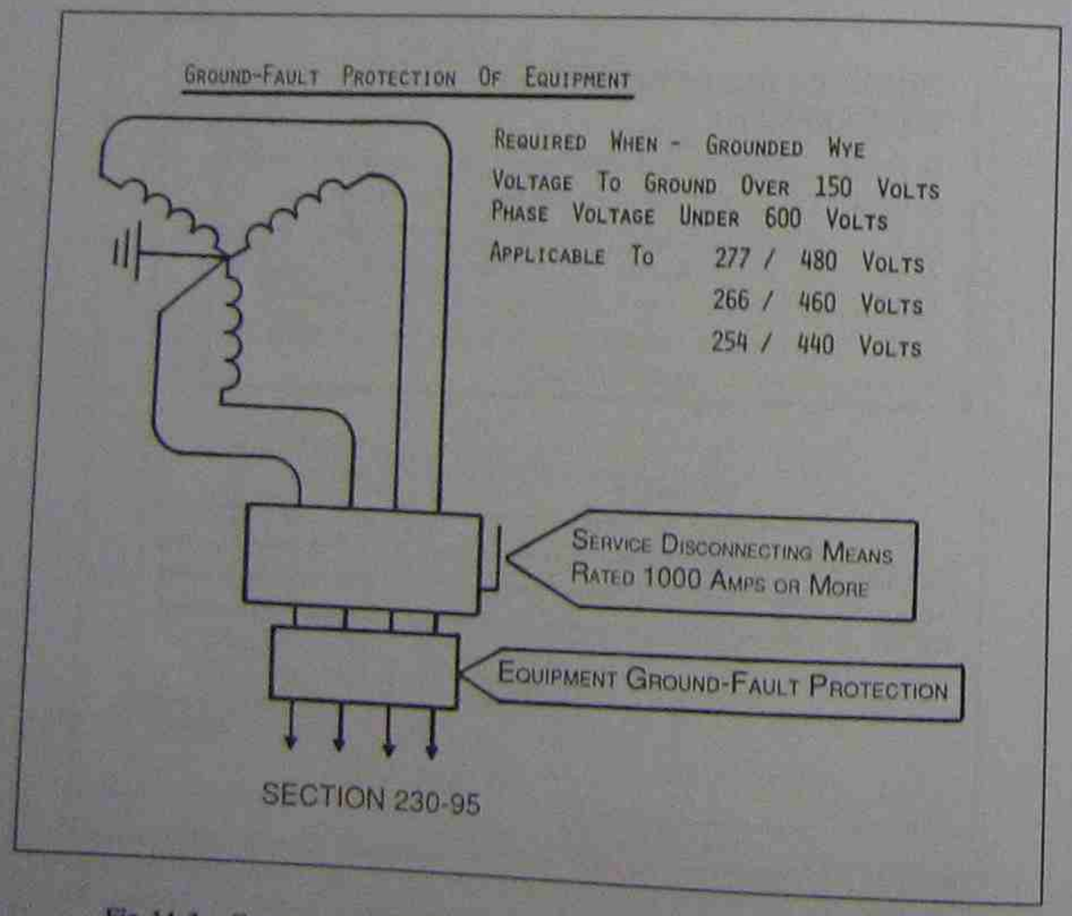


Fig. 14–3 Ground-fault protection of equipment is required by *Section 230-95*.

Pinpointing the wye connection eliminates the delta or delta-with-a-grounded-leg connection. The limitations of over 150 volts to ground and under 600 volts between phases almost pinpoints the 277/480, nominal voltage, wye connection. The 120/208-volt wye connection is less than 150 volts to ground.

Figure 14–4 illustrates the use of two service disconnecting means, each rated at 800 amps. Although the total is 1600 amps, the service is not required to have ground-fault protection. However, ground-fault protection is permitted on 277/480-volt, wye connected systems with less than a 1000-amp service disconnecting means.

Figure 14–5 illustrates the use of a 1000-amp switch with 800-amp fuses in it. This is classified as a 1000-amp disconnect, and ground-fault protection is required. The Fine Print Note (FPN) to *Section 250-95* identifies the service disconnecting means rating when fuses are used or a circuit breaker is used for the overcurrent protection.

1. The rating of the disconnecting means is determined by the largest fuse that can be installed in the disconnecting switch.
2. The rating of the disconnecting means is determined by the higher trip setting for which the actual overcurrent device installed in a circuit breaker is rated or can be adjusted.

There are two exceptions where the ground-fault protection is not required, should the situation qualify for exemption. These are:

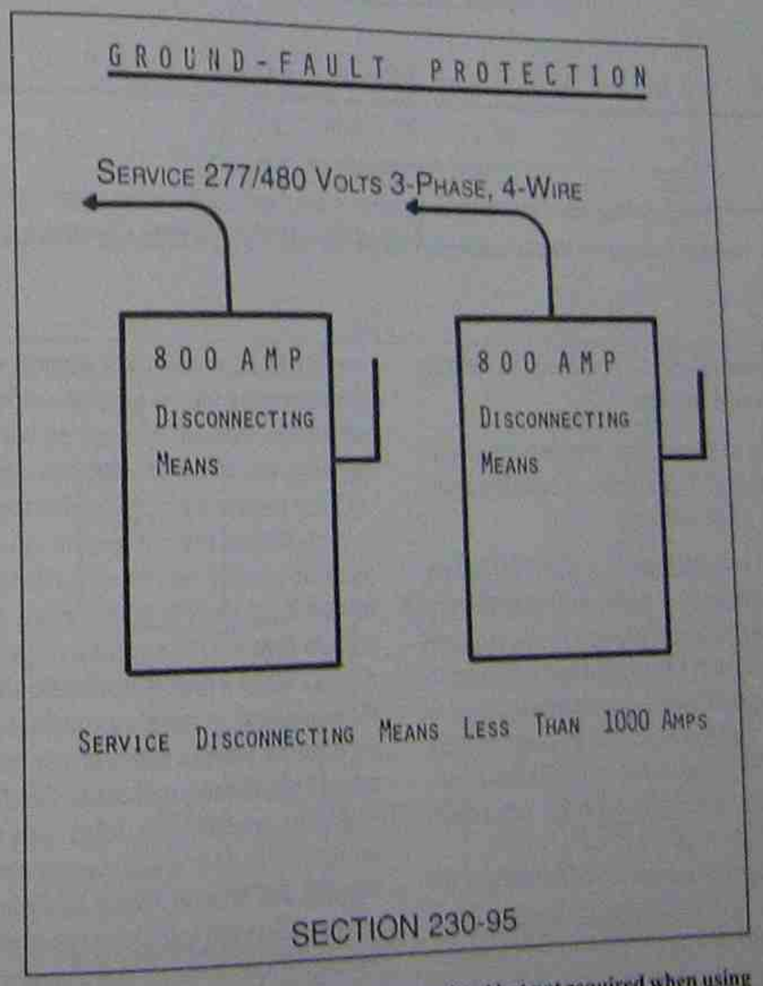


Fig. 14–4 Ground-fault protection is permitted but not required when using two 800-amp service disconnecting switches.

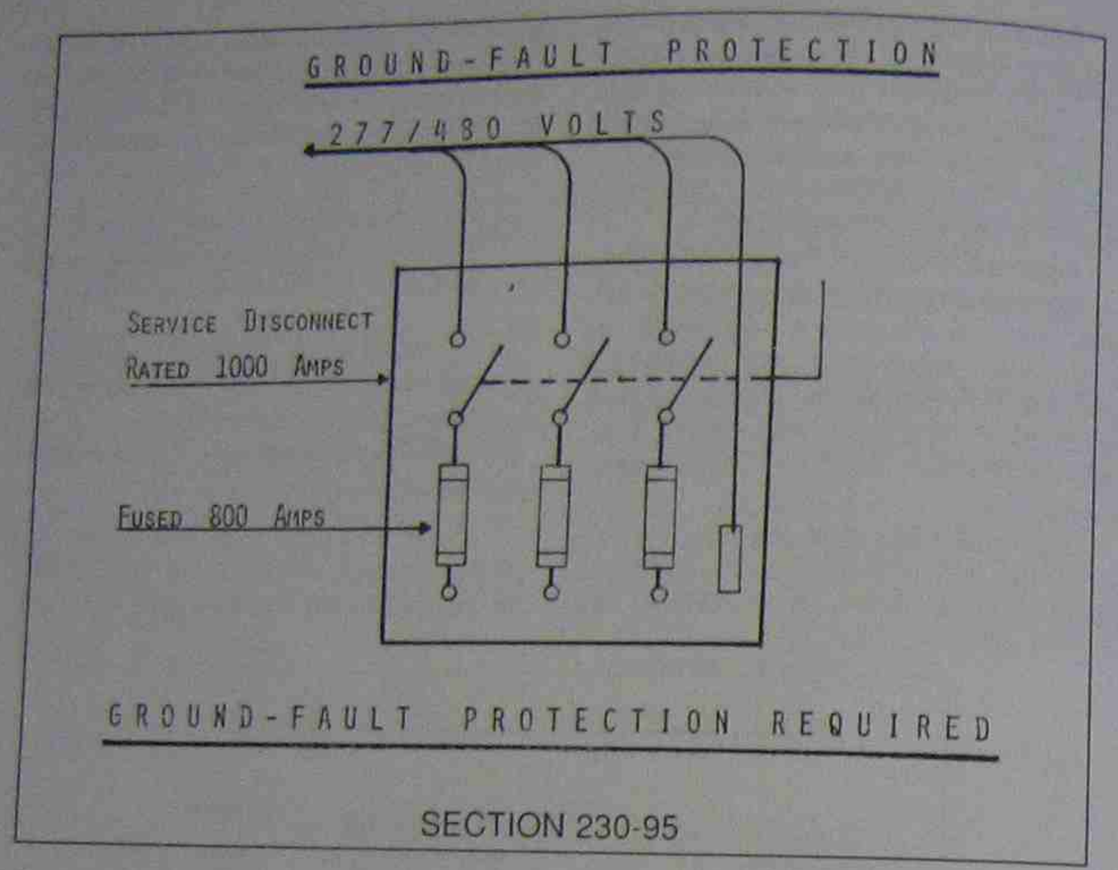


Fig. 14–5 Ground-fault protection is required at the service when using a 1000-amp switch with 800-amp fuses.

1. An industrial process where an orderly shutdown is needed
2. A supply to a fire pump where there is need for the pump motor to keep running under any and all conditions

Figure 14–6 illustrates a 277/480, three-phase, four-wire service with a 600-amp disconnecting means. This installation is not required to have ground-fault protection but it is permitted to have ground-fault protection. The requirement in *Section 230-95* is only for the service, but a FPN indicates it would be advantageous to also have ground-fault protection downstream (figure 14–7).

The principle of operation of the magnetic-window type ground-fault protector (figure 14–2) has all the phase conductors and the neutral passing through an iron ring. When there is more current going out on the circuit than is coming back, the sensing device will cause the disconnecting means to open, taking the service off the line. Just an unbalanced current situation between the phase conductors and the neutral will not trigger the sensing device.

A second type of ground-fault protection used to protect services is illustrated in figure 14–8. A current transformer monitors the current flow on the equipment grounding conductor. When a predetermined current flows on the equipment grounding conductor, the secondary of the current transformer will activate a relay. This, in turn, will cause the disconnecting means to operate. The relay can also be connected so it will sound an alarm instead of tripping the breaker. Note in figure 14–8 how any current in the equipment grounding conductor must flow through the current transformer before reaching the grounding electrode conductor or the grounded conductor.

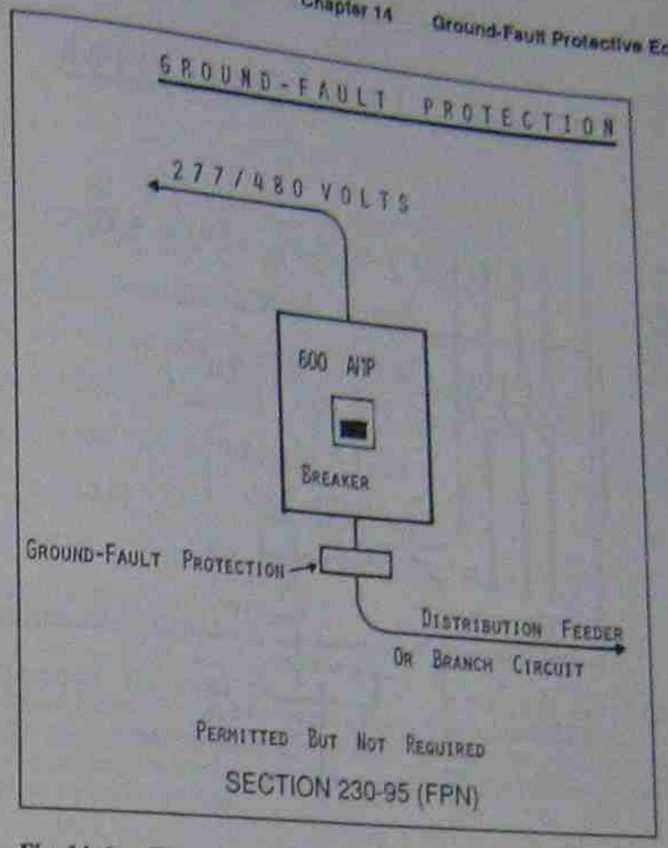


Fig. 14–6 When the service switch is rated at less than 1000 amps, ground- fault protection is not required.

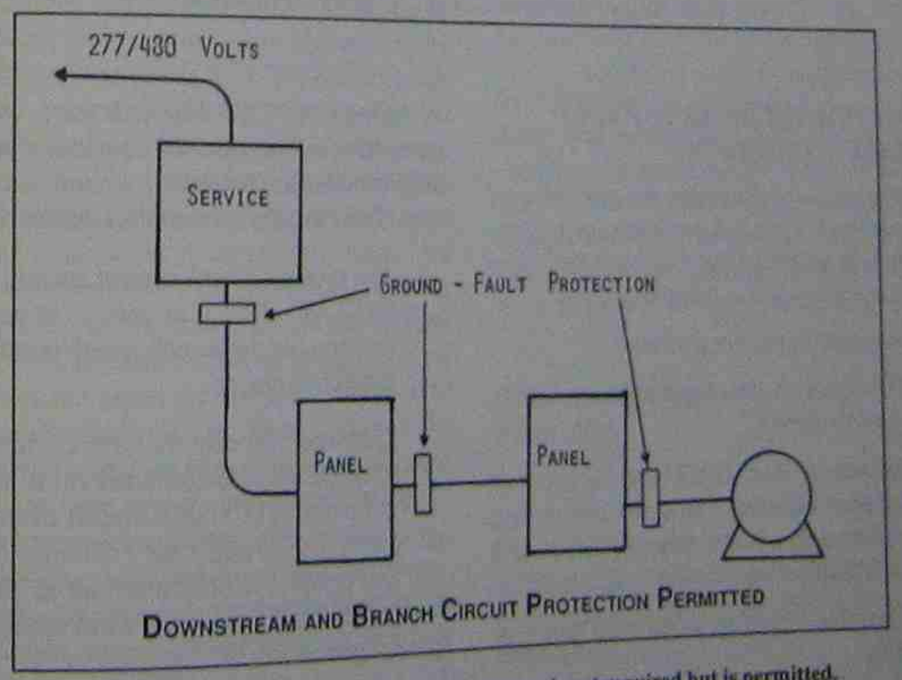


Fig. 14–7 Downstream ground-fault protection is not required but is permitted.

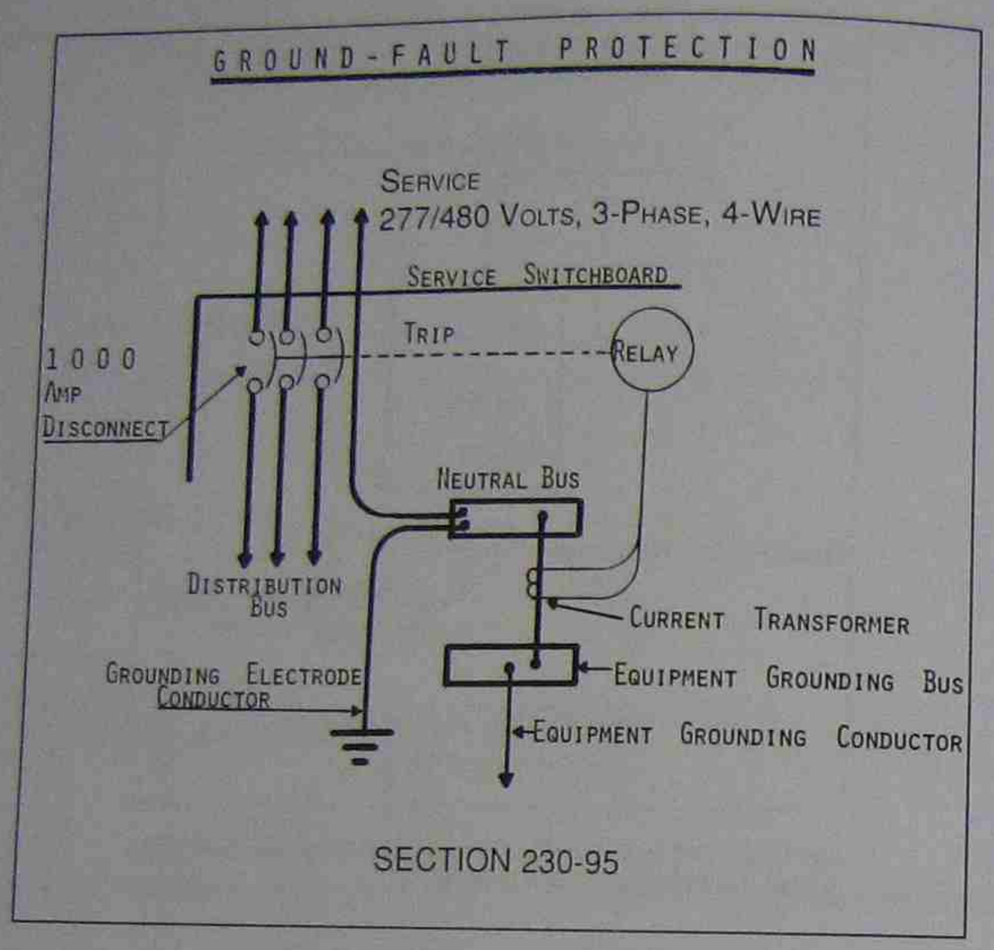


Fig. 14–8 Using a current transformer for ground-fault protection.

DEFINITION OF *GROUND-FAULT CIRCUIT INTERRUPTER*

Figure 14–9 illustrates the definition of *Ground-Fault Circuit Interrupter*, usually referred to as a *GFCI*. The following lists some important points in the definition:

1. Intended to protect personnel
2. Functions to de-energize a circuit or a portion thereof

Comment: The GFCI can be a circuit breaker that will clear the entire circuit or a device that will protect only one outlet or a number of outlets on a circuit.

3. Operates within an established period of time

Comment: This time can vary with the manufacturer, but is usually considered to be 30 milliseconds (30/1000 of one second) to comply with Underwriters Laboratories standards.

4. The predetermined current setting of the GFCI will allow it to operate at less than the rating of the branch circuit overcurrent protective device.

Comment: To comply with Underwriters Laboratories, the predetermined value here is 4 to 6 milliamps. The branch circuit overcurrent protective device might be a 20-amp breaker and will protect the branch circuit at 20 amps, but the GFCI will function at 4 to 6 milliamps to protect personnel.

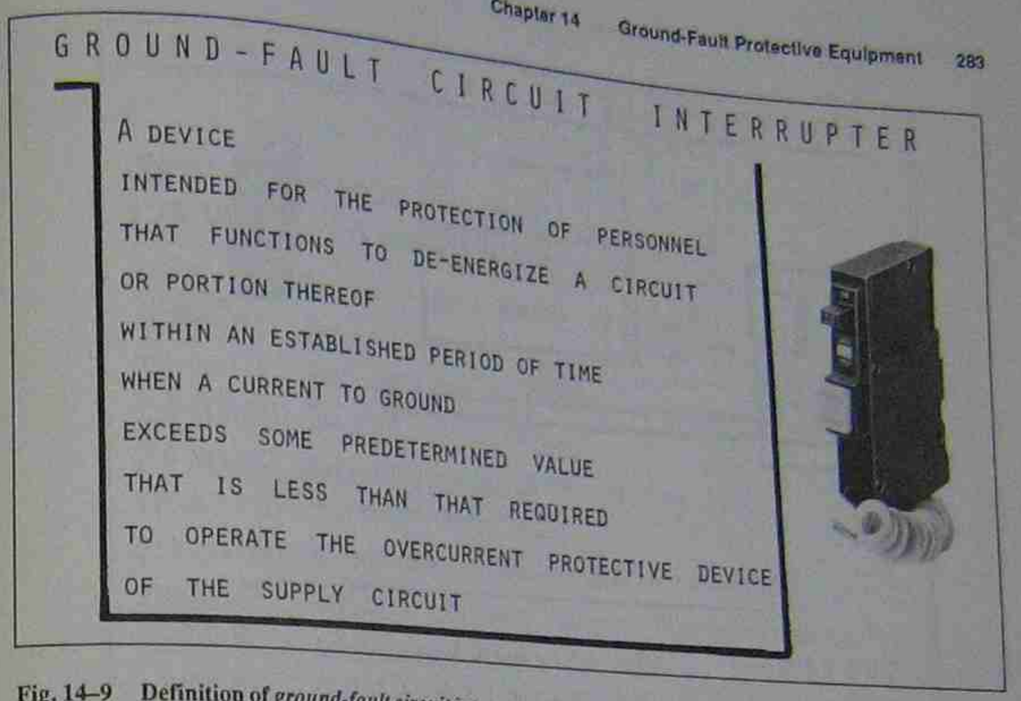


Fig. 14–9 Definition of *ground-fault circuit interrupter*. Reprinted with permission from NFPA 70-1987, National Electrical Code, Copyright © 1986, National Fire Protection Association, Quincy, MA 02269. This material is not the complete and official position of the NFPA on the referenced subject, which is represented only by the standard in its entirety. Photo courtesy Square D Company.

Theory of Operation

Figure 14–10 illustrates a breakdown of a ground-fault circuit interrupter. A breaker is illustrated, but the principle of operation is the same for an individual GFCI. The hot conductor and the neutral conductor must be installed together as they pass through a differential transformer. The transformer uses a magnetic field to measure the amount of current going to the load against the current returning from the load. The strength of a magnetic field is directly proportional to the current flowing in the conductor. When the amount of current going to the load does not equal the current returning from the load, the induction in the secondary of the differential transformer causes the sensing unit to operate. The sensing unit causes the circuit breaker or the device to trip and open the circuit.

Circuits protected by a GFCI breaker require two conductors to the circuit. There are no three-phase, four-wire circuits for GFCIs for personnel protection.

The GFCI does not protect someone against receiving a shock, but it does limit the time the hazard exists (figure 14–11). The danger still exists, even when there is a GFCI in the circuit. And when an individual receives a shock, the surprise of the shock may cause an injury. For example, an individual might be outside on a metal ladder working with an electric tool and receive an electric shock through the defective tool. Before the GFCI could operate, the surprise shock could cause the individual to fall from the ladder.

Receptacles Requiring GFCI Protection

Figure 14–12 lists the locations required by the Code where installed receptacles must have GFCI protection. The requirement can be fulfilled if the branch circuit has a GFCI breaker or an individual GFCI is installed at the particular location.

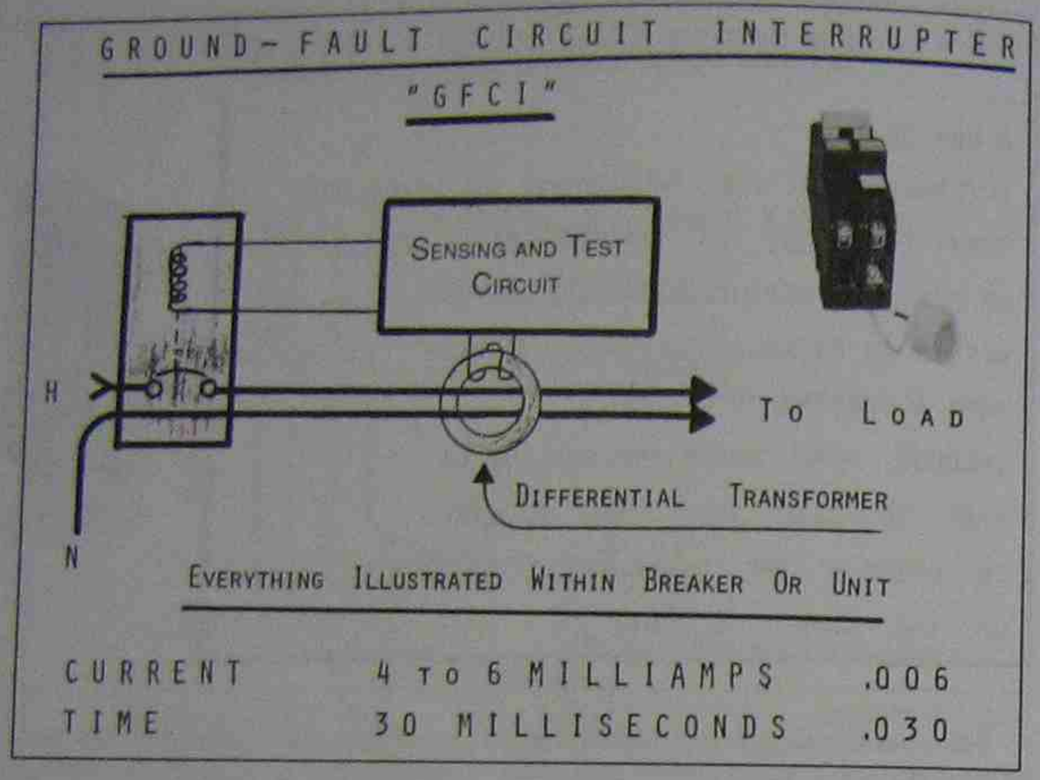


Fig. 14–10 **GFCI theory of operation.** Courtesy Eaton Corporation "Cutler-Hammer" Products.

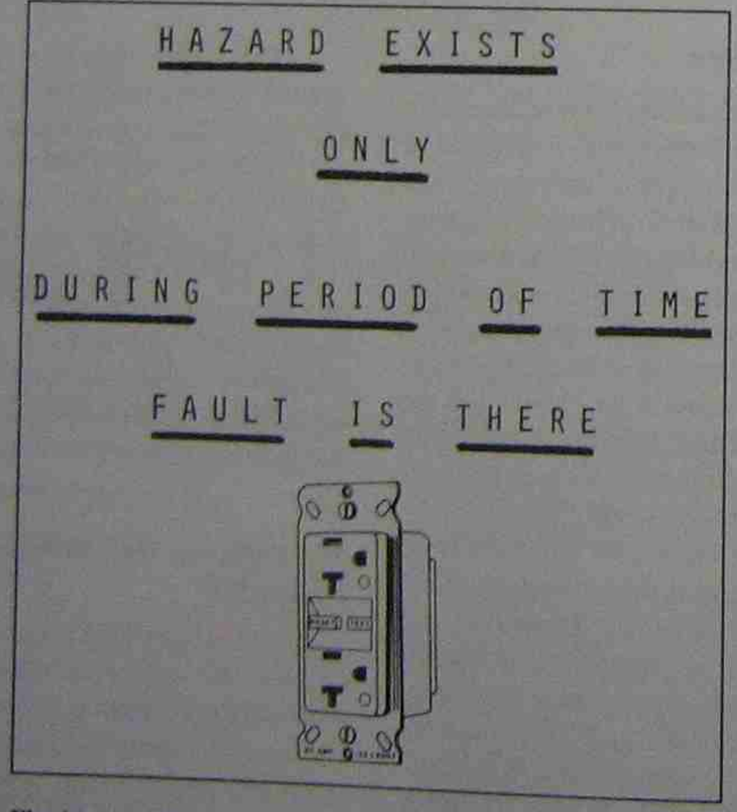
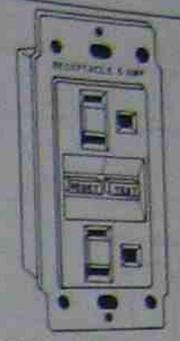


Fig. 14–11 **Electric shock hazard exits only during the period of time that the fault is there.**



GFCI Receptacles Required 125 Volts – 15 and 20 Amps

210-8(a)(1)	Dwelling - Bath Area
210-8(a)(2)	Dwelling - Garage
210-8(a)(3)	Dwelling - Outdoor - Ground Level
210-8(a)(4)	Dwelling - Basement
210-8(a)(5)	Dwelling - Within 6 Ft Kitchen Sink
210-8(a)(6)	Dwelling - Boat House
210-8(b)	Motel - Hotel - Bath Area
210-52(f)	Dwelling - Detached Garage - Power Available
305-4	Construction Sites - Temporary
422-8(d)(3)	Portable High Pressure Spray Washing Machine
511-10	Commercial Garages - Diagnostic Equipment Electrical Hand Tools - Portable Lighting Devices
517-90(c)	Health Care - Patient Care Area Wet Locations
550-6(b)	Mobile Homes - Bath - Lavoratory
550-53	Mobile Home Parks - Outdoors
551-7(c)	Recreation Vehicles - Bath - Lavoratory
551-42	Recreation Vehicle Parks - Outdoors
555-3	Marinas & Boatyards Other Than Shore Power
680-6	Swimming Pools Within 20 Feet Of Inside Of Pool

Fig. 14–12 **Receptacles required to be GFCI protected.**

Figure 14–13 illustrates the use of a ground-fault receptacle to replace an ungrounded receptacle, as permitted by the exception to *Section 210-7(d)*. Note the last portion of this exception, which prohibits an equipment grounding conductor from being connected from the GFCI receptacle to any other outlet supplied downstream from the GFCI receptacle.

Section 210-8 lists several locatio GFCIs are required to be installed. Eac installations starts out with one specific r ment in common:

all 125-volt,
single-phase,
15- and 20-ampere receptacles

and ends with the same statement:

protection for personnel.

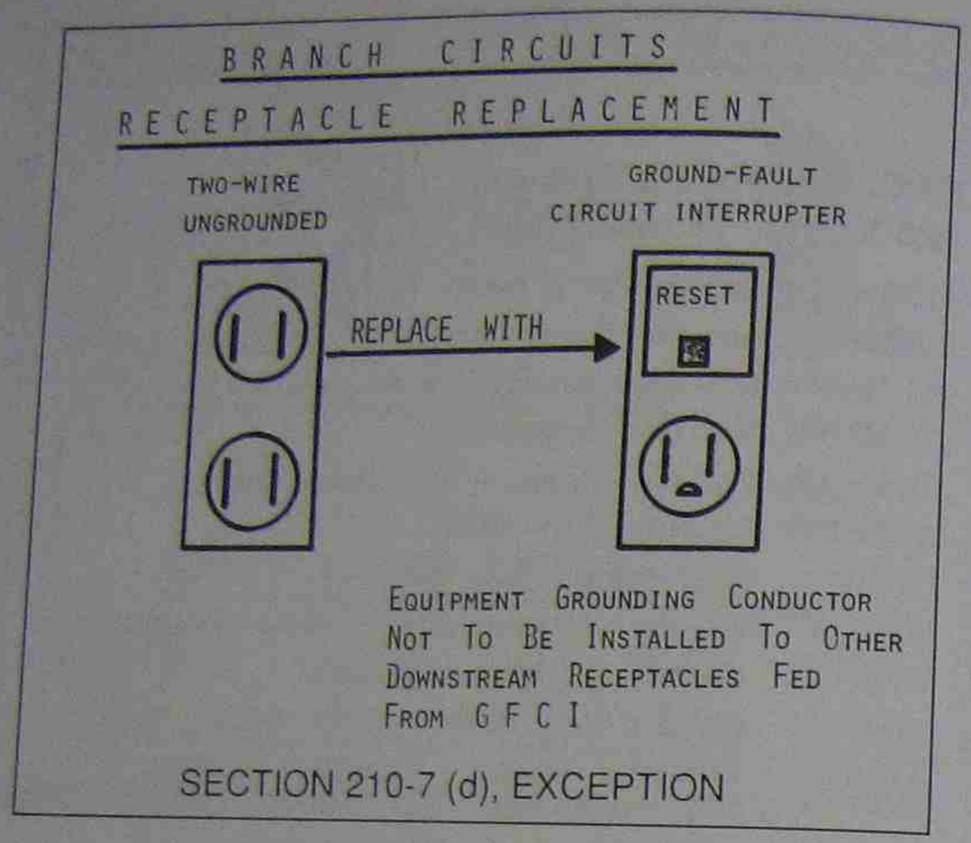


Fig. 14–13 GFCI used for replacement of a two-wire receptacle in dwelling units.

Figure 14–14 illustrates a receptacle in-
ed in a bathroom of a dwelling unit. The
e requires one GFCI receptacle to be in-
ed near the washbowl in each bathroom.
ld there be more than the one required
tacle installed in a bathroom, all extra
lled receptacles shall be GFCI protected.
Section 210-8(a)(2) (figure 14–15) re-
s all receptacles installed in attached ga-
of a dwelling unit to have GFCI protec-
Exception No. 1 to *Section 210-8(a)(2)*
to receptacles that are not readily acces-
The phrase "not readily accessible" per-
stalling a receptacle without GFCI pro-
in the ceiling of a garage for an overhead
erator, or any other receptacles that are
d and are not readily accessible. Excep-
. 2 allows cord- and plug-connected
ent occupying dedicated space to be
d without GFCI protection when the
d plug connection is used for changing or
g the equipment or preventing transmis-
sion of vibration or noise. When there is more than one receptacle installed in an attached garage not covered by Exceptions No. 1 or No. 2, all must be GFCI protected.

Figure 14–16 illustrates a detached garage for a dwelling unit with a ground-fault receptacle installed in the garage. If there is no electrical power carried to the detached garage, there is no requirement for a receptacle to be installed in the detached garage. However, when power is carried to the detached garage, such as for the installation of a light, a receptacle shall be installed, and it shall be GFCI protected. Any additional receptacles installed in the detached garage would be affected by the requirements of *Section 210-8(a)(2)* and its exceptions, as illustrated in figure 14–15. *Section 210-52(f)* requires a receptacle to be installed in a residential garage. *Section 210-8(a)(2)* requires receptacles installed in residential garages to have ground-fault protection.

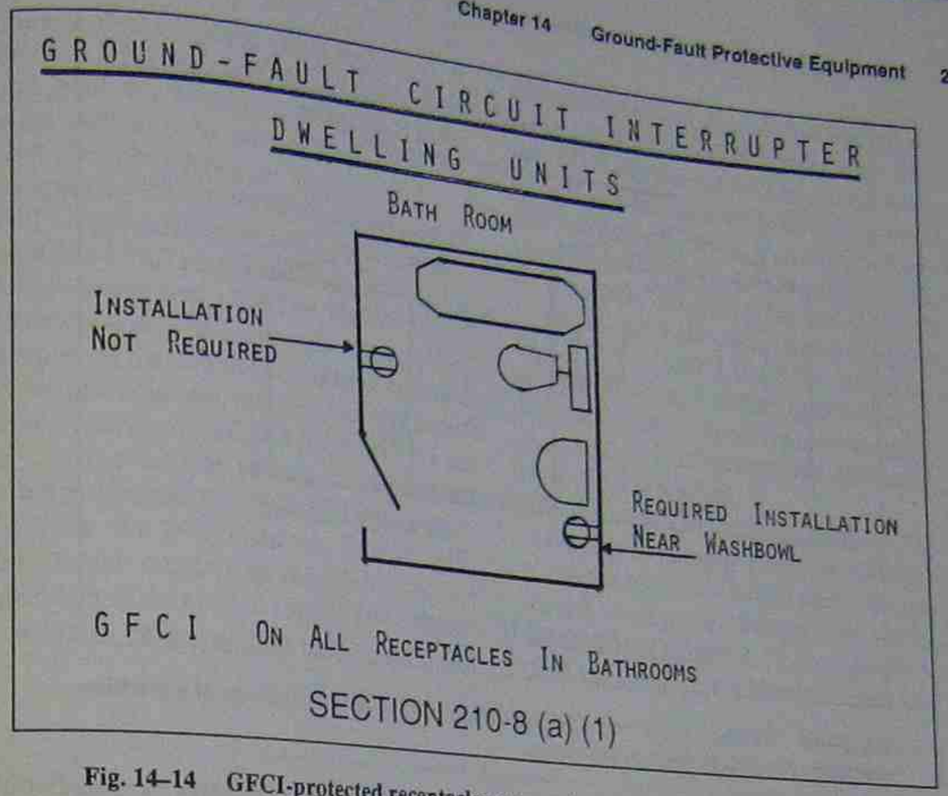


Fig. 14–14 GFCI-protected receptacles are required in bathrooms of dwelling units.

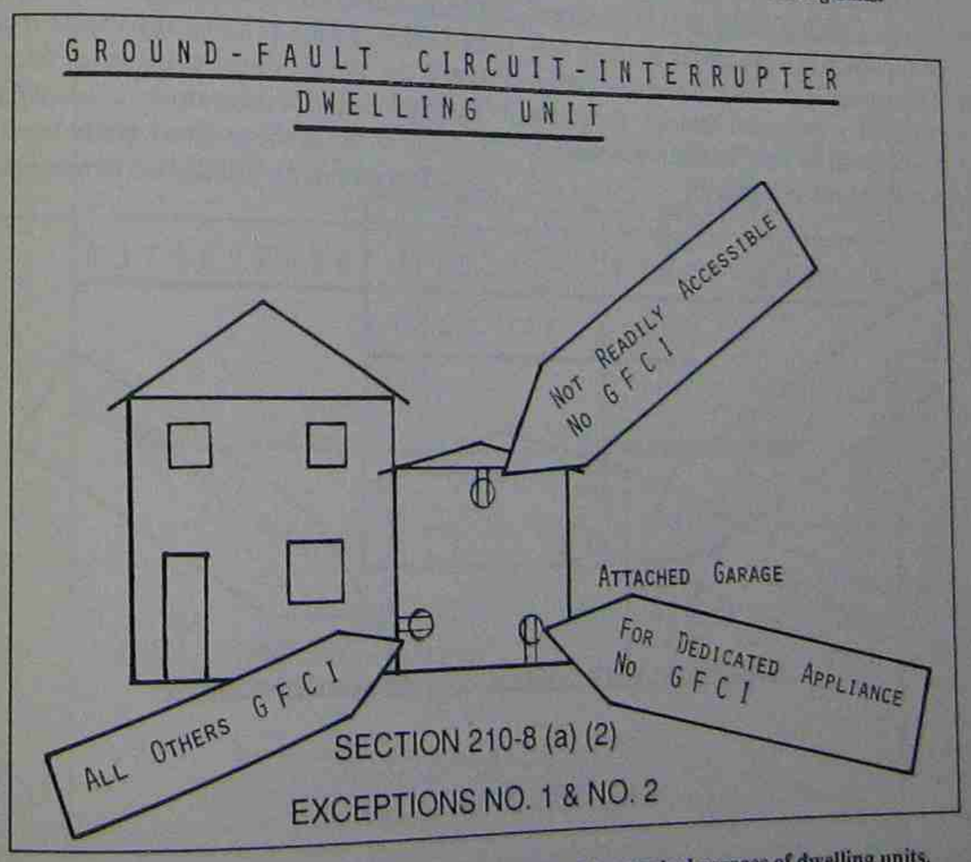


Fig. 14–15 GFCI-protected receptacles are required in attached garages of dwelling units.

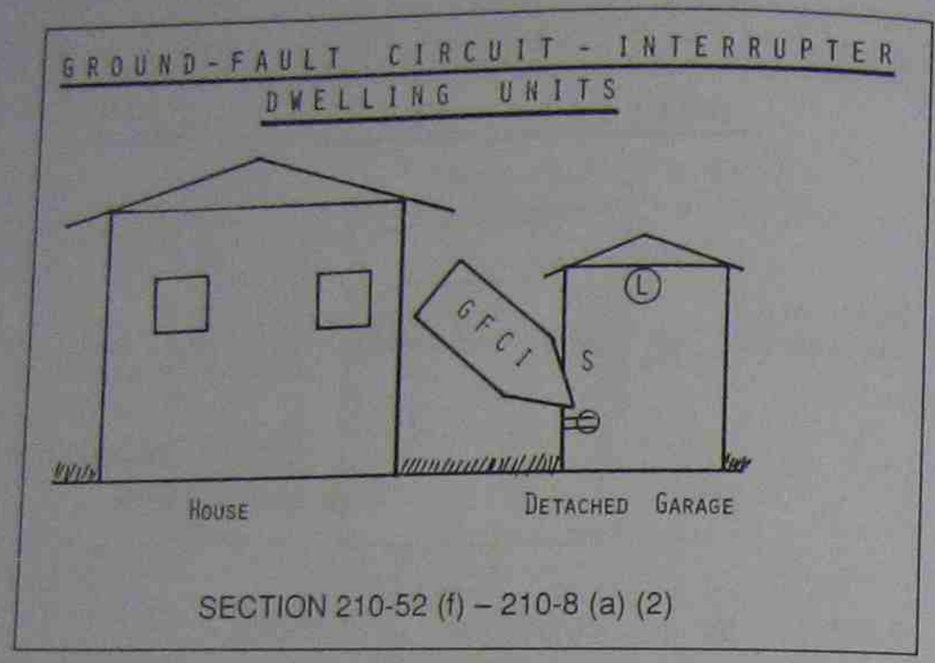
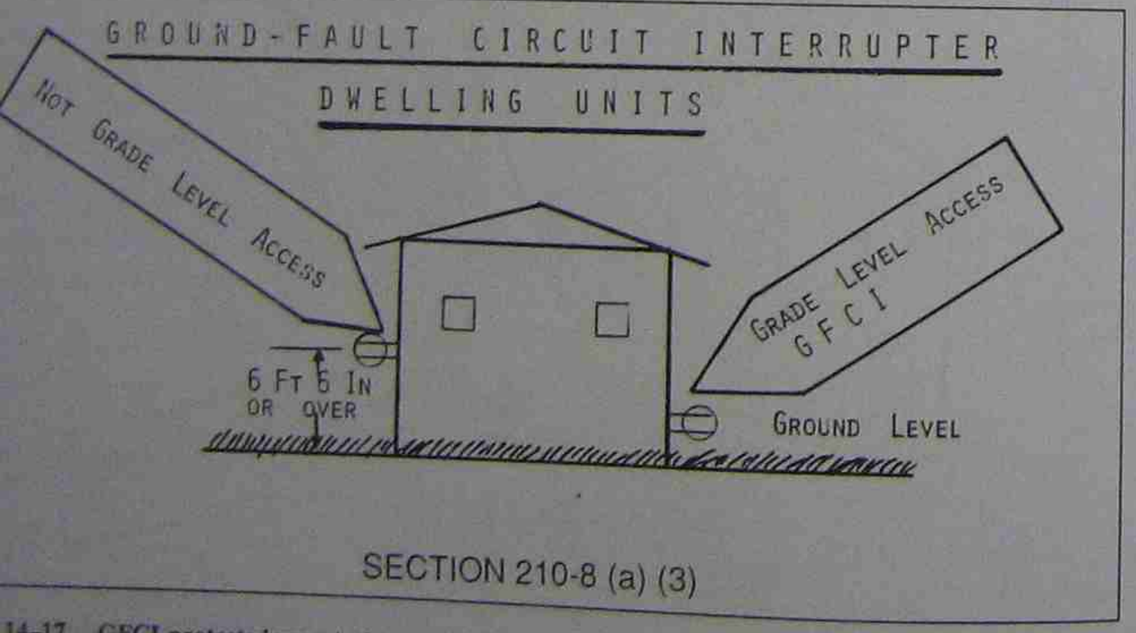


Fig. 14–16 GFCI-protected receptacles are required in a detached garage of a dwelling unit when power is brought to the garage.

Reasons: It is too easy to plug an extension ord into an outlet in a garage and use an electric ool or appliance in a hazardous situation out- de of the garage. The concrete floor of a garage considered a grounded surface. Defective ectric tools can be a real hazard when making tomobile repairs in a garage.

Figure 14–17 illustrates the installation of GFCIs outdoors for a dwelling unit, as required by *Section 210-8(a)(3)*. The key to this regulation is the phrase "direct grade level access." The requirement specifies an elevation of 6 feet, 6 inches as being above direct grade level access. This permits the installation of receptacles



14–17 GFCI-protected receptacles are required outdoors when at grade-level access of dwelling units.

on outdoor decks without GFCI protection, if the receptacles are at least 6 feet, 6 inches above ground level. It also permits receptacles to be installed outdoors on second-floor balconies without GFCI protection.

Figure 14–18 illustrates the installation of a GFCI in the basement area of a dwelling unit. At least one GFCI receptacle shall be installed in the basement and it shall be identified as a GFCI receptacle. This does not limit the number of receptacles that are permitted to be installed in a basement, but only requires that one receptacle in a basement be GFCI protected. By the same token, the Code permits all receptacles installed in basements to be GFCI protected.

Figure 14–19 illustrates *Section 210-8(a)(5)*, which requires all receptacles located within 6 feet of the kitchen sink, above countertop surfaces, of a dwelling unit to be GFCI protected. It is very possible that more than one receptacle could be within 6 feet of the kitchen sink. If so, all shall be GFCI protected. Any sink located in other than the kitchen of a dwelling unit, such as a bar sink, is not covered by this regulation. The Code does not require a receptacle installed close to a bar sink to be GFCI protected, but it also permits that receptacle to be GFCI protected. The FPN indicates that receptacles located closer than 6 feet to the kitchen sink but dedicated to an electrical appliance, such as a refrigerator, are not required to have GFCI protection.

Figure 14–20 illustrates *Section 210-8(a)(6)*, which requires a receptacle installed in a boathouse to be GFCI protected. This requirement is listed under dwelling units and has the intent of requiring a GFCI receptacle where there is a damp or wet location. Therefore, this

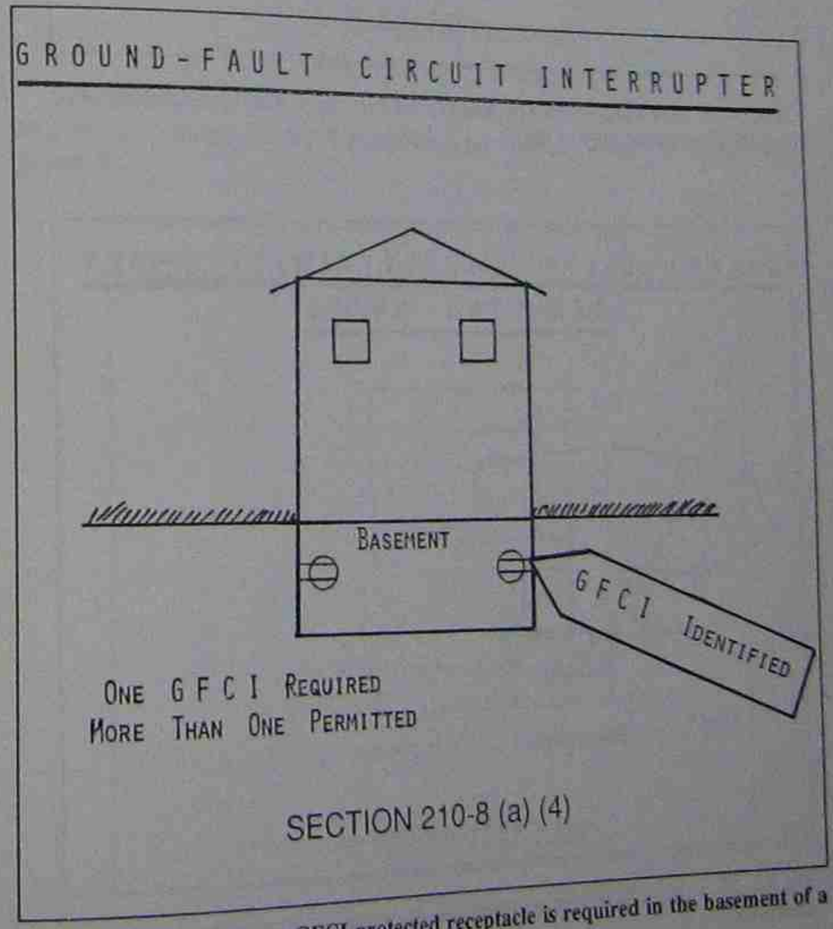


Fig. 14–18 At least one GFCI-protected receptacle is required in the basement of a dwelling unit.

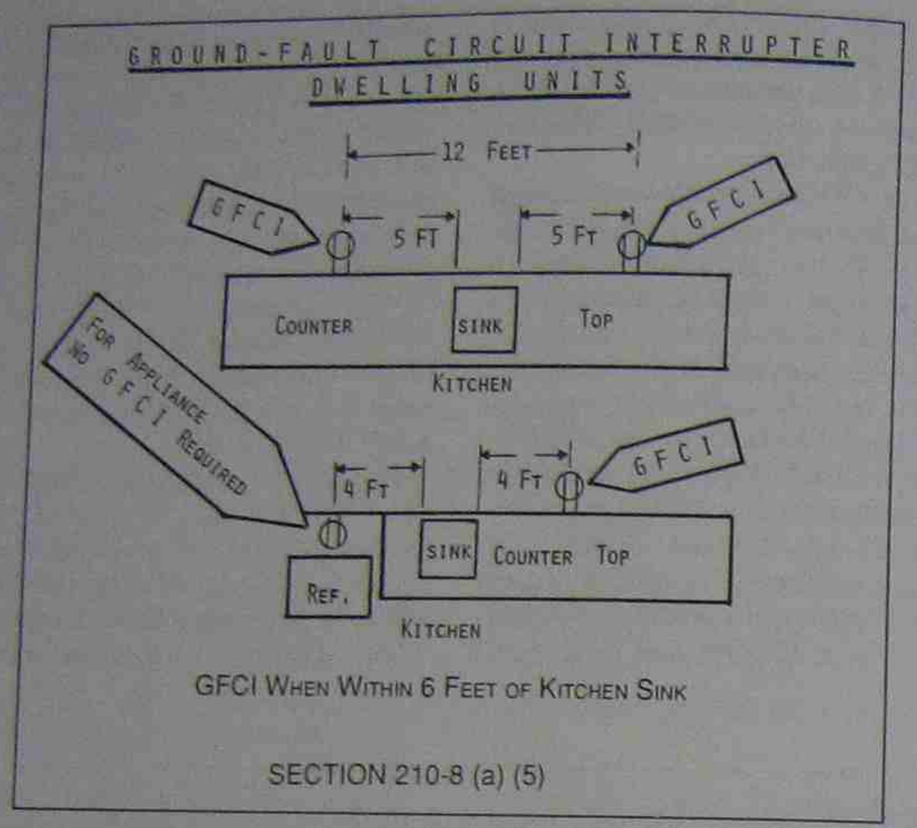


Fig. 14–19 GFCI protection is required for kitchen countertop receptacles installed within 6 feet of the kitchen sink.

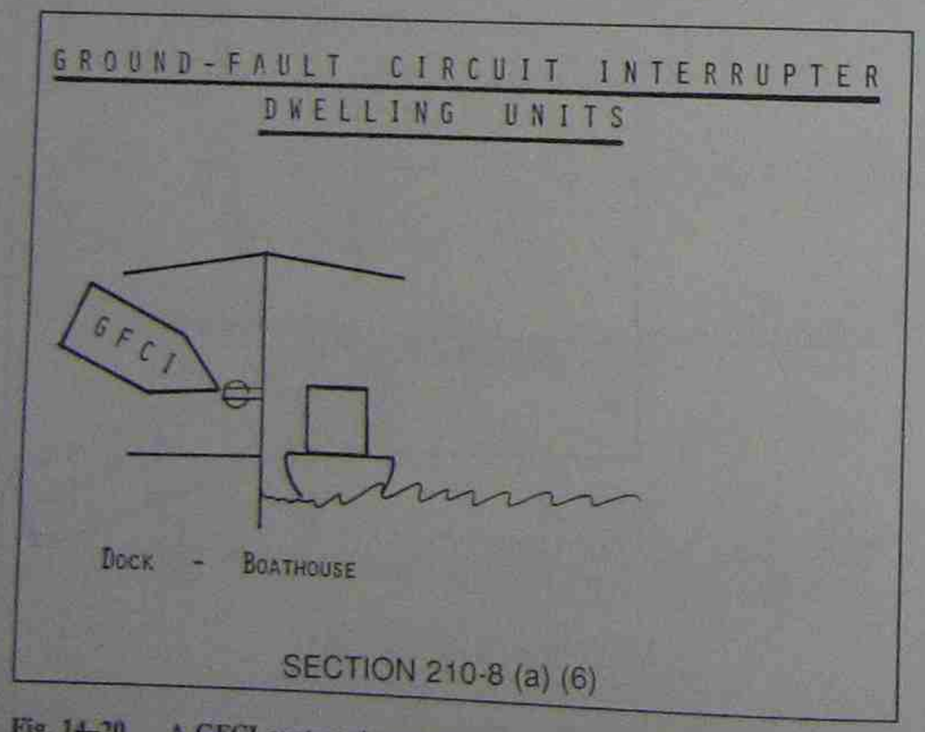


Fig. 14–20 A GFCI-protected receptacle is required for a residential dock or boathouse.

would apply to a dock or boathouse that is constructed as part of a dwelling unit and has electrical power brought to it.

Section 215-9 refers to *Section 210-8* and indicates, as illustrated in figure 14–21, that receptacle GFCI protection required by *Section 210-8* need not be installed when the feeder has GFCI protection.

Figure 14–22 illustrates *Section 210-8(b)*, the requirement for GFCI-protected receptacles in bathroom areas of motels and hotels. Often the tub or shower and commode are installed in

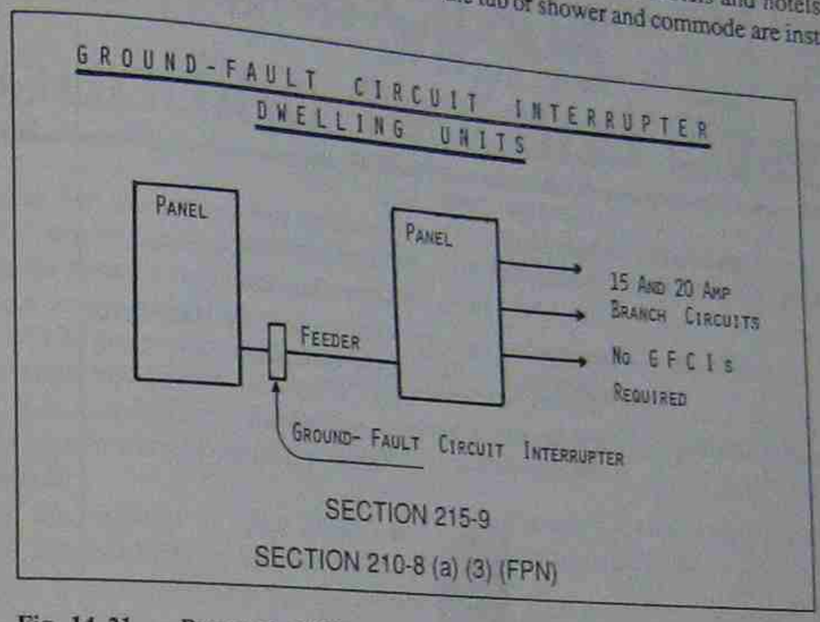


Fig. 14–21 Receptacle GFCI protection is not required when a feeder has GFCI protection.

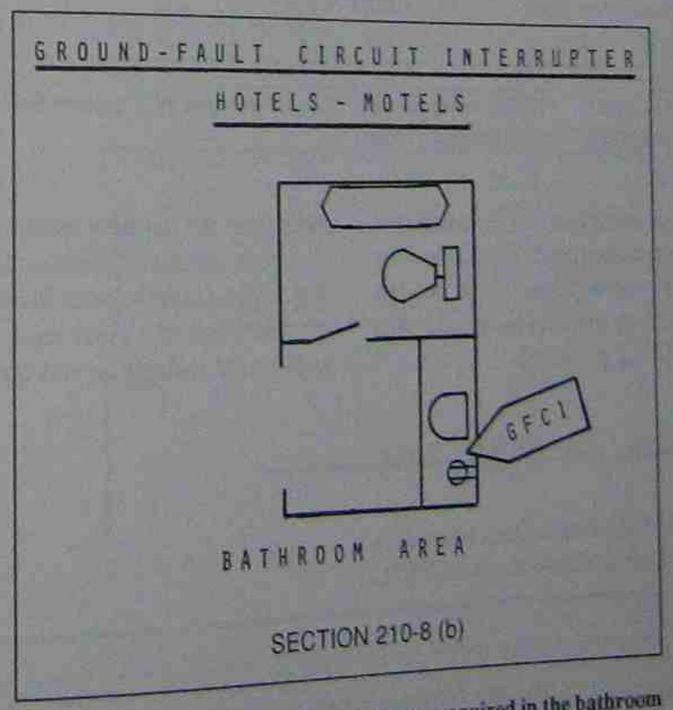


Fig. 14–22 GFCI-protected receptacles are required in the bathroom area of hotels and motels.

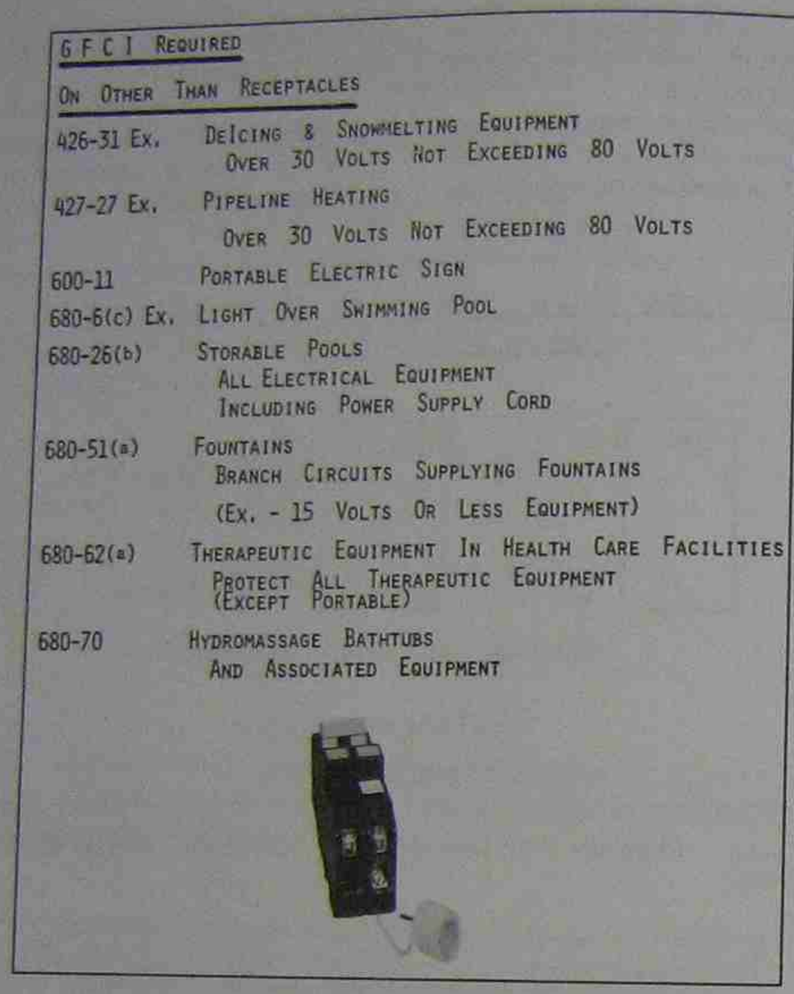


Fig. 14–23 GFCIs required other than for receptacles. Courtesy Eaton Corporation "Cutler-Hammer" Products.

what technically is one room and the washbowl is installed in a separate room. The Code does not consider these two separate rooms but one "bath area," and the receptacles installed in this area all shall be GFCI protected.

Note from the list how these requirements are located in various articles throughout the Code. A close look at the list also illustrates the Code's concern when electrical equipment is located and/or used in damp or wet locations.

GFCI Required for Other Than Receptacles

Figure 14–23 lists installations, other than receptacles, for which the Code requires GFCIs.

CHAPTER 15

System and Circuit Grounding 1 kV and Over

Chapter 7 of this text covered the requirements for alternating-current system and circuit grounding for systems under 1000 volts, which are the more common installations. Now special attention will be given to grounding alternating-current systems and circuits 1 kV (1000 volts) and over, such as a 4160-volt, three-phase, wye connected system with the center tap intentionally grounded.

Why are systems of over 1000 volts grounded? The Fine Print Note to *Section 250–1* answers this question. Systems and circuits are solidly grounded for several reasons. These are:

1. To limit the voltage due to lightning
2. To limit the voltage due to line surges
3. To limit the voltage due to unintentional contact of the supply with higher voltage lines
4. To stabilize the voltage to ground during normal operation
5. To facilitate the operation of the overcurrent device in case of ground fault

These are the same reasons that lower voltage circuits are grounded.

NEUTRAL GROUNDED SYSTEMS

There are three systems used for grounded neutral systems 1000 volts and over, and each will be covered separately. They are:

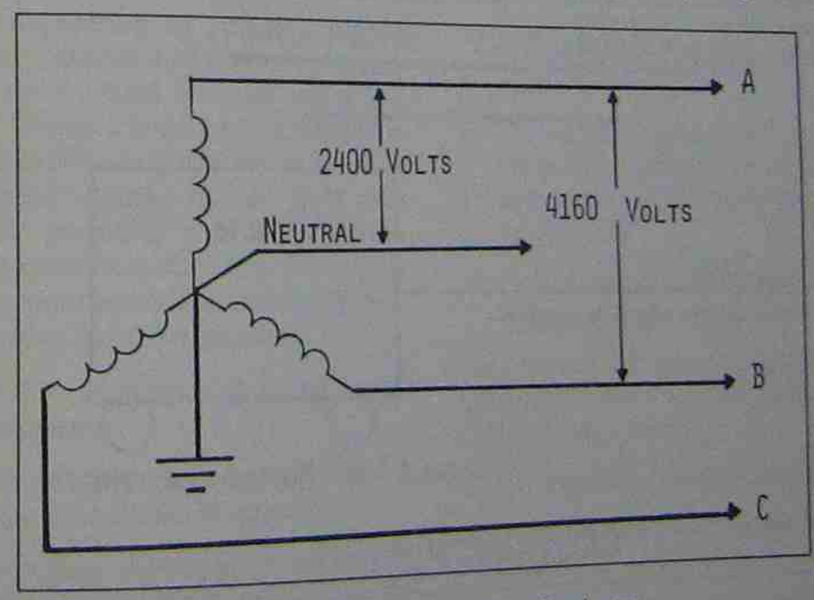


Fig. 15–1 Grounding systems 1 kV and over.

1. Transformer-grounded neutral systems
2. Solidly grounded neutral systems
3. Impedance-grounded neutral systems

The key to understanding grounding for circuits 1 kV and over is in *Section 250-5(c)*. The only time the Code requires high-voltage systems to be grounded is when the system supplies portable or mobile equipment (figure 15–2). All other high-voltage systems are not required to be grounded but are permitted to be grounded. Figure 15–3 illustrates a 4160-volt motor in a stationary location that is not required to have a grounded supply. However, the supply is permitted to be grounded.

NEUTRAL GROUNDED SYSTEMS REQUIRED AND PERMITTED

Section 250-5(c) makes three special points for grounding systems 1000 volts and over. These are:

1. AC systems of 1000 volts and over supplying mobile or portable equipment are required to be grounded.

   Comment: The details for accomplishing this requirement are contained in *Section 250-154*.

2. AC systems of 1000 volts and over supplying other mobile or portable equipment are permitted to be grounded.

   Comment: It is interesting to note that any other system operating at 1000 volts or over is permitted with or without a grounded neutral system when the system does not supply portable or mobile equipment.

3. When 1000-volts-and-over systems are installed with a grounded neutral, all applicable sections of *Article 250* apply.

   Comment: The applicable provisions of *Article 250* cover such things as the materials and types of connections; these are repeated at the beginning of Part M. This part indicates that systems of over 1000 volts, when grounded, shall be installed in accordance with the applicable provisions of *Article 250*. For example, the grounding electrode conductor will be installed the same for either a system over 1000 volts or one under 1000 volts.

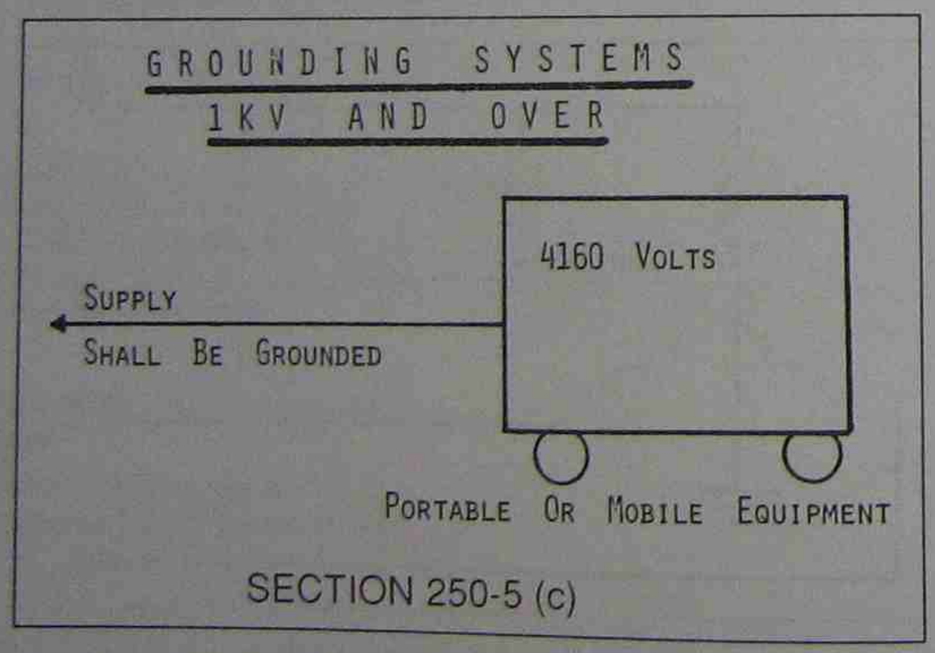


Fig. 15–2 Grounding high-voltage systems when they supply portable and mobile equipment.

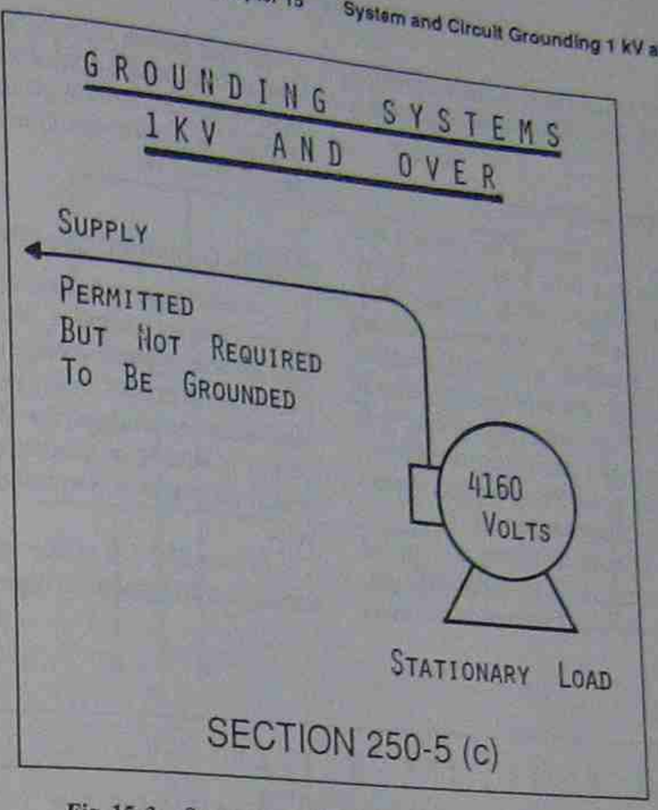


Fig. 15–3 Systems over 1 kV are permitted to be grounded.

Portable or Mobile Equipment

The requirement for portable or mobile equipment operating at 1000 volts or over to be supplied by a neutral grounded system was given in *Section 250-5(c)* and is repeated in *Section 250-154*, along with how this shall be accomplished. *Section 250-154* gives more details for grounding high-voltage systems supplying portable or mobile equipment, other than substations installed on a temporary basis. The following lists the requirements:

1. It shall have its neutral grounded through an impedance.
2. When a delta connected system is used, a system neutral shall be derived.
3. The voltage developed by the flow of maximum ground fault current is limited to 100 volts between the portable or mobile equipment frame and ground.
4. Any high-voltage system component developing a ground fault shall be automatically de-energized by ground fault detection and relaying.
5. The grounding electrode shall be isolated from and separated in the ground by at least 20 feet from any other equipment grounding electrode.
6. No direct connection is permitted between buried pipe or fence electrodes.

Comment: This really narrows the supply system for portable or mobile equipment to two supply systems. These are:

1. An impedance neutral grounded system
2. A system with a neutral grounding transformer

Note the mandatory statement "to automatically de-energize." This does not permit the

use of an audio or visual alarm and then manual operation of the system disconnecting means.

Grounding Transformers

Section 250-151 permits the use of a system neutral, derived from a grounding transformer, to ground high-voltage systems. Figure 15–4 illustrates the use of a wye connected transformer to establish a neutral grounded point. The secondary of a supply transformer is an ungrounded, delta connected system. It is connected directly to a grounding transformer, which establishes a neutral grounded system through the grounding transformer.

Figure 15–5 illustrates the use of a zig-zag transformer connection to establish the grounded neutral system. The three-phase, delta connected system utilizing a grounding transformer of either the wye or zig-zag connection is permitted for neutral grounded systems for portable or mobile equipment, as outlined by *Section 250-154*.

Solidly Grounded Systems

A solidly grounded system is illustrated in figure 15–6, as permitted in *Section 250-152*, with a phase-to-phase voltage of 4160 volts and 2400 volts to ground or the neutral. The phase conductors are insulated for 5000 volts but the neutral is already at ground potential, so the neutral insulation is permitted to be only 600 volts.

Section 250-152 covers the installation of a solidly neutral grounded high-voltage system.

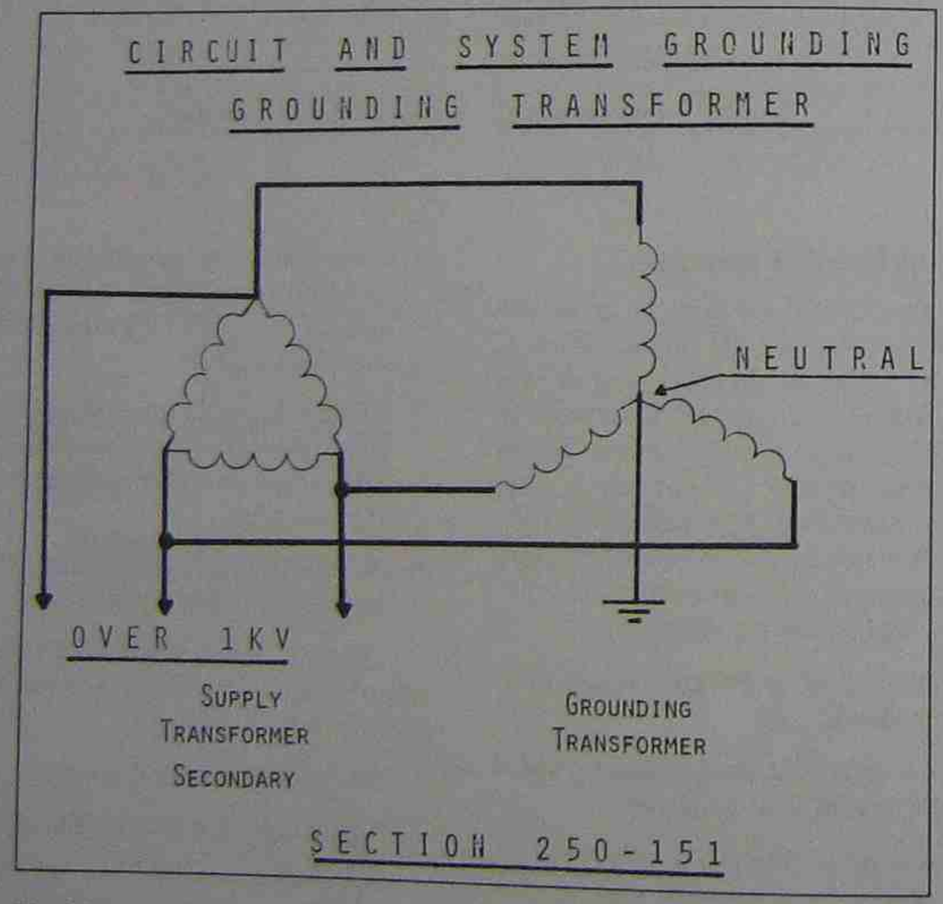


Fig. 15–4 Circuit and system grounding when using a wye connected grounding transformer.

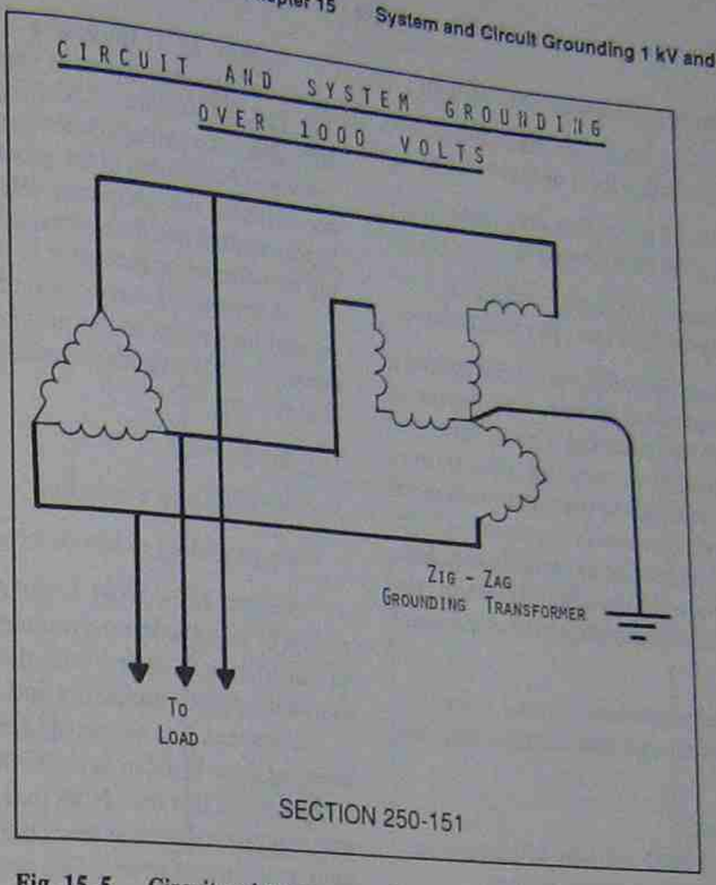


Fig. 15–5 Circuit and system grounding when using a zig-zag connected grounding transformer.

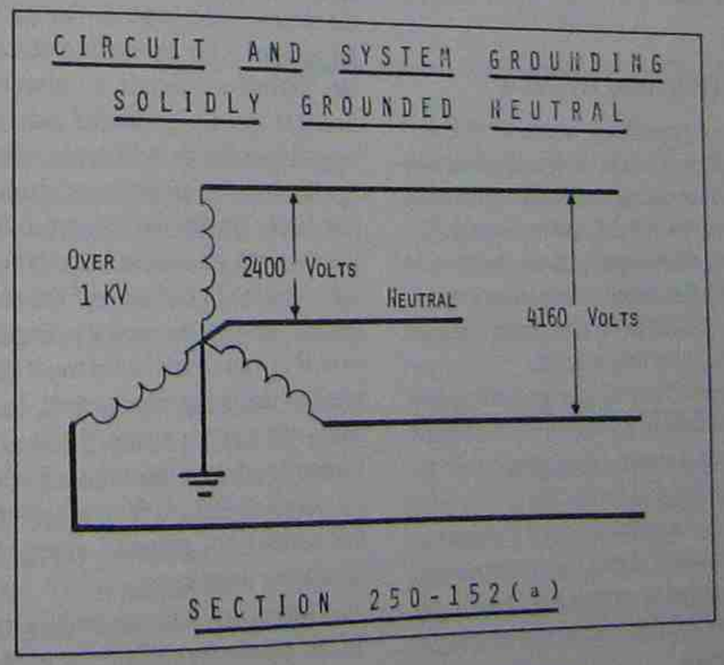


Fig. 15–6 Solidly grounded neutral system.

All the following conditions shall be met:

1. The neutral conductor shall have a minimum insulation level of 600 volts.
2. The neutral grounding conductor is permitted to be bare when it is
   a. isolated from phase conductors,
   b. and protected from physical damage.

Comment: The solidly grounded neutral is the same potential as ground. The purpose of using the 600-volt insulation is to have just enough insulation to keep the neutral from touching ground, such as when it is run in metal raceways, and to establish a ground path for circulating currents. The exceptions to *Section 250-152(a)* allow the use of a bare neutral conductor when installed underground or overhead outdoors.

3. The solidly grounded neutral system is permitted to be grounded at more than one point for
   a. services,
   b. direct buried portions of feeders employing a bare copper neutral,
   c. overhead portions of feeders installed outdoors.

Impedance Grounded Systems

Impedance grounding means there is opposition to current flow (impedance) intentionally connected in series with the grounding electrode conductor and the system neutral. The impedance will intentionally limit the current flow to ground. A resistor or impedance coil is used and both are referred to as "impedance" because of the alternating current.

The purpose of impedance grounding is to limit the current flow to ground in case of a fault, thereby offering a measure of protection for equipment from ground faults. By limiting the current flow, the arc at the point of fault can be eliminated or limited. This is one of the reasons the neutral grounded system is required for use with portable or mobile equipment operating at 1000 volts or more.

Figure 15–7 illustrates an impedance-grounded neutral system, as permitted by *Section 250-153. Section 250-153(a)* requires the impedance for an impedance-grounded neutral system to be inserted in the grounding conductor between the grounding electrode of the supply system and the neutral point of the supply transformer or generator.

Comment: The term *grounding conductor* as used here refers to the grounding electrode conductor. The impedance must be connected in series with

- the neutral,
- the grounding electrode,
- the grounding electrode conductor.

Section 250-153(b) further requires the neutral of an impedance-grounded neutral system to be fully insulated with the same insulation as the phase conductors and identified.

Comment: The means of identification can be any of those listed in *Article 200* and covered in chapter 8 of this text. Note that for an impedance neutral grounded system, the neutral originates at the transformer. The neutral only extends from the center point of the wye to the line side of the grounding resistor. The line side of the resistor is the neutral. The grounded side of the resistor is the grounding electrode conductor. Therefore, there is a voltage between the line side and the grounded side of the system neutral impedance, which also results in a voltage between the neutral and ground. The voltage from the neutral to ground will be the voltage drop across the impedance, which will vary with the impedance of the resistor and the current flowing through the impedance. However, the neutral conductor must be insulated the same as the phase conductors. In the case of a 4160-volt system using 5 kV insulation, the neutral conductor must have 5 kV insulation.

Section 250-153(c) prohibits connecting the neutral to ground, except through the grounding impedance.

Comment: The neutral is not used as a circuit conductor, which it is with a solidly grounded system.

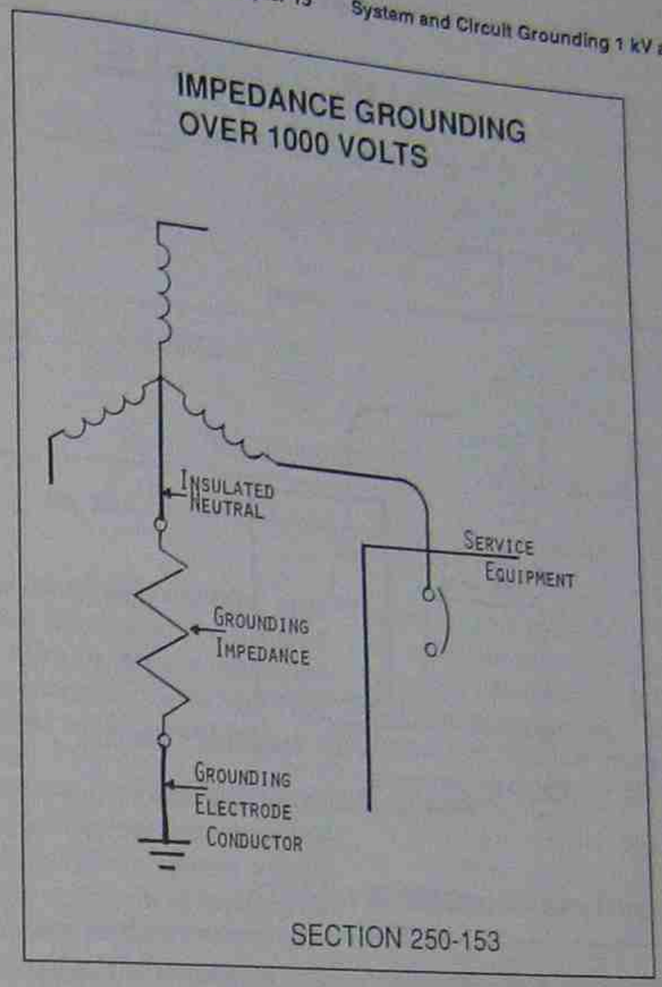


Fig. 15–7 Impedance grounded neutral system.

Section 250-153(d) is directed at the equipment grounding conductor for high-voltage systems. The conductor is permitted to be bare. It is required to be connected to the ground bus and the grounding electrode conductor at the service-entrance equipment and extended to the system ground.

Comment: This is the same requirement made for grounding systems under 1000 volts. All the grounding conductors are brought to one point and the grounding electrode conductor connects them to the grounding electrode.

CAUTION: The neutral is NOT connected to the grounding electrode conductor. The conductor connected to the grounded side of the grounding impedance is connected to the grounding electrode conductor. The equipment grounding conductor is not connected to the neutral at the service or ahead of the grounding impedance, but to the grounding electrode conductor on the grounded side of the grounding impedance (figure 15–8) *(Section 250-153.)*

EQUIPMENT GROUNDING

The grounding of high-voltage equipment is extended to cover the housings and fencing containing high-voltage current-carrying equipment. *Section 250-155* requires noncurrent-carrying metal parts of high-voltage equipment to be grounded. This includes the following:

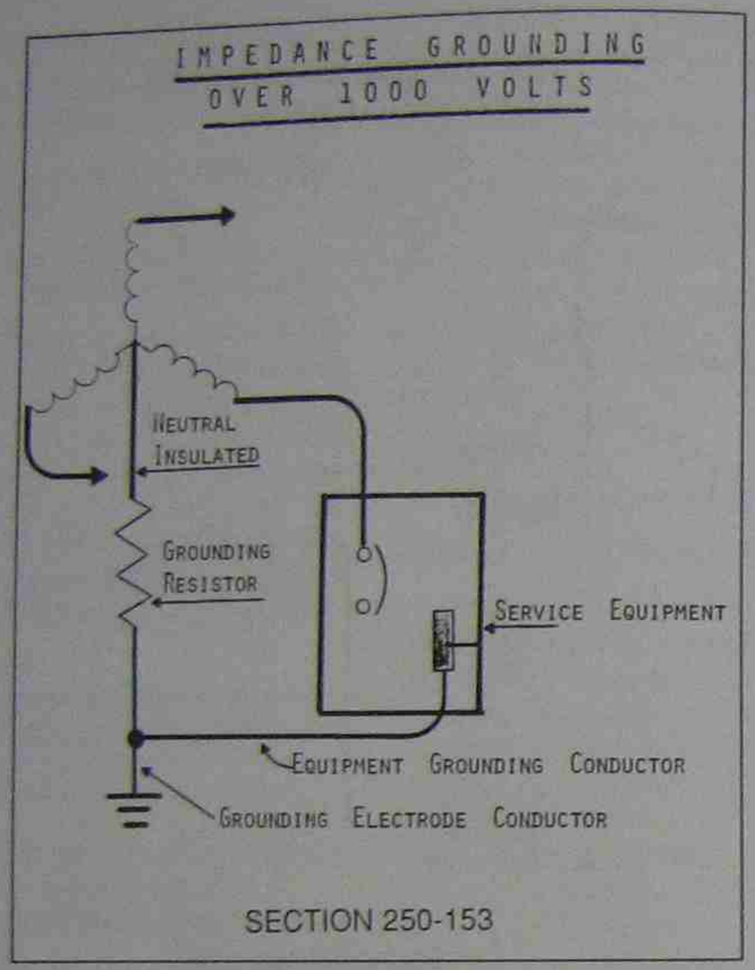


Fig. 15–8 Equipment grounding conductor connection in a neutral impedance grounded system.

1. Fixed equipment
2. Portable equipment
3. Mobile equipment
4. Associated fences
5. Equipment housings
6. Equipment enclosures
7. Conductor enclosures
8. Supporting structures

The equipment grounding conductor, when not an integral part of a cable assembly, shall not be smaller than:

1. No. 6 copper
2. No. 4 aluminum

High-voltage equipment is not required to be grounded when it is isolated from ground and located so it prevents any person who can make contact with ground from contacting such metal parts when the equipment is energized. Such equipment is not required to be grounded when it is elevated and is used for pole-mounted distribution equipment.

Table 250-95 shows the equivalent equipment grounding conductor for a 200-amp circuit. Therefore, a 60-amp or 100-amp circuit will be required to have the minimum grounding conductor. Circuits rated at over 200 amps shall have their equipment grounding conductor sized according to *Table 250-95*.

Where there is a solidly grounded system, the equipment grounding conductor is

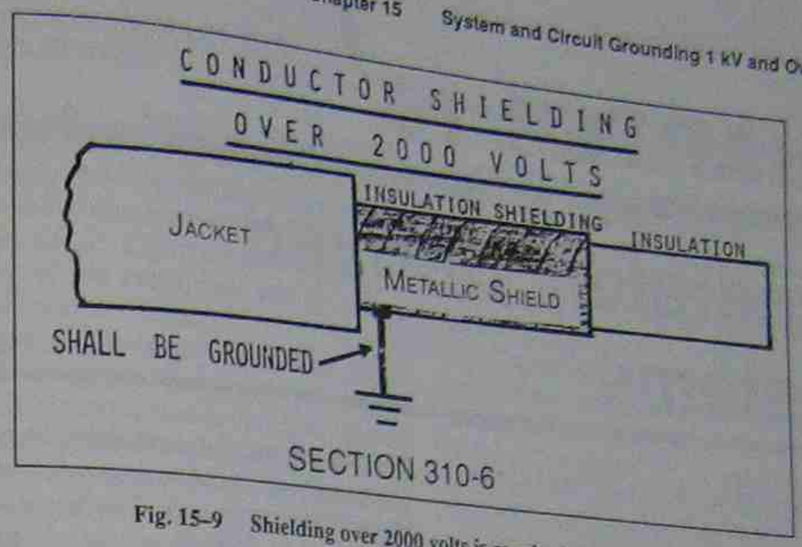


Fig. 15–9 Shielding over 2000 volts is required to be grounded.

connected the same as for systems under 1000 volts. Where there is an impedance-grounded system, caution must be taken in making the connection. The connection must be made to the grounding electrode conductor and not to the neutral conductor.

Section 250-154(d) protects against the loss of continuity of the equipment grounding conductor for high-voltage systems feeding portable or mobile equipment by requiring the equipment grounding conductor to be monitored for continuity. It shall be continuously monitored for continuity. Upon loss of continuity of the equipment grounding conductor, the high-voltage feeder is automatically de-energized.

This regulation illustrates the importance placed on the equipment grounding conductor by requiring the monitoring of the continuity of the equipment grounding conductor. The second thing this regulation indicates is that a system supplying portable or mobile equipment shall not be operated unless the equipment grounding conductor is in place and has continuity.

Grounding Shielded High-Voltage Cable

Figure 15–9 illustrates a shielded cable with the shield grounded to confine the voltage stresses to the insulation caused by high voltage, as required by *Section 310-6*. All high-voltage shielded cable operating at over 2000 volts shall have the insulation shield grounded with an effective grounding path.

CHAPTER 16

Separately Derived Systems

A good way to look at a separately derived system is as another supply system, other than the utility company supply. The separately derived system might be a generator with a gas or diesel engine for the prime mover, an alternator converter, a motor generator set, or a transformer with no electrical connection between the primary and the secondary. Figure 16–1 illustrates some of the various ways to create a separately derived system. The most common of the separately derived systems is the transformer. This chapter focuses on Code regulations for separately derived systems of less than 1000 volts.

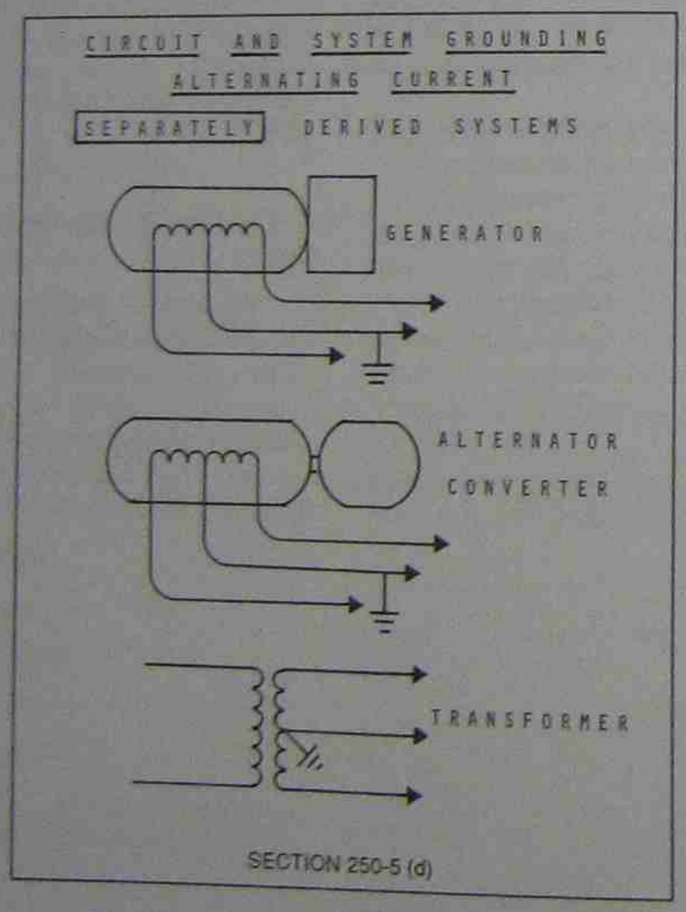


Fig. 16–1 Creating a separately derived system.

DEFINITION OF *SEPARATELY DERIVED SYSTEM*

Figure 16–2 illustrates a separately derived system, as covered in *Section 250-26*, with the secondary of the transformer connected wye and a grounded center tap for the neutral. The Code does not put it in so many words, but the secondary of the transformer can be treated almost as another service.

A gas engine-operated generator that is used for emergency or standby power upon failure of the normal or utility company system can be a separately derived system, provided the neutral is not common to both the normal and the standby supply. Figure 16–3 illustrates a normal supply and a standby supply using an automatic transfer switch. Note that the neutral is switched and is not a common conductor through the transfer switch. Therefore, the standby system is a separately derived system.

Figure 16–4 illustrates a normal system with a standby system and a transfer switch. The transfer switch does not break the neutral conductor. The neutral conductor is solidly connected to both the normal and the standby supplies. Therefore, the Fine Print Note to *Section 250-5(d)* says that this is not a separately derived system because the neutral is common to both supplies.

Figure 16–5 illustrates a two-winding transformer with no electrical connection between the primary and secondary of the transformer. The neutral of the transformer's primary and the neutral of the transformer's secondary are completely separate. The 120/240-volt secondary of the transformer is a separately derived system.

There is no electrical connection built into a transformer between the primary and secondary of the transformer (other than auto-transformers), and there are no connections made in

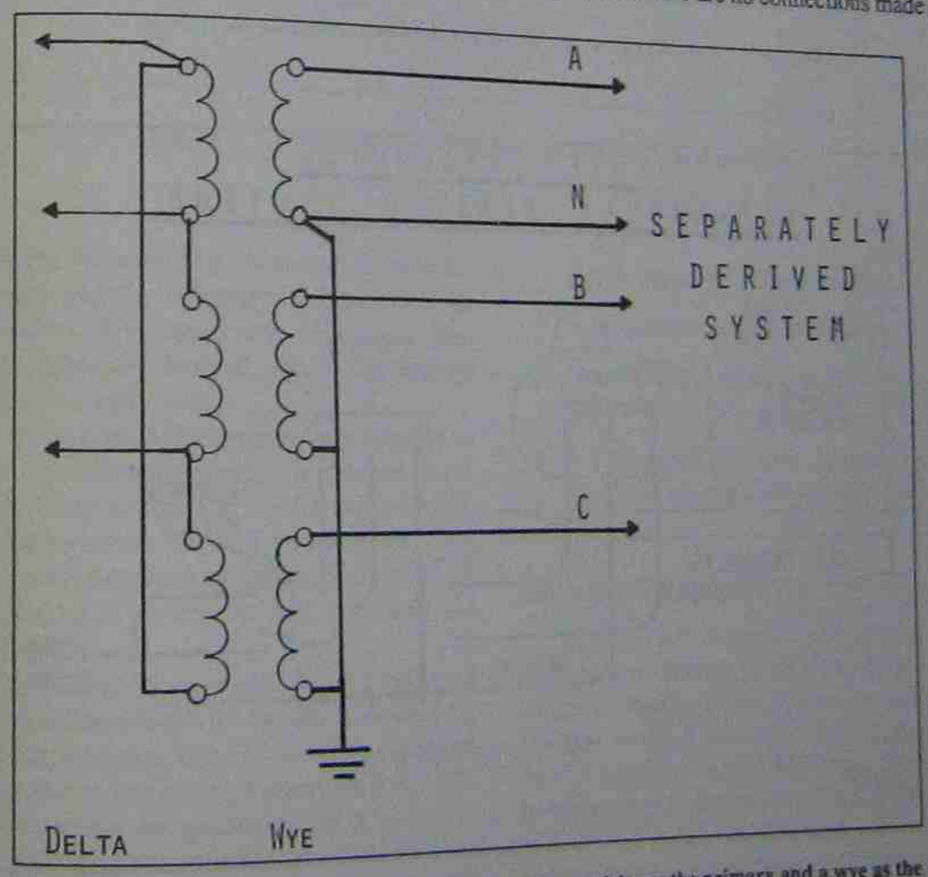


Fig. 16–2 A separately derived system with a transformer delta as the primary and a wye as the secondary.

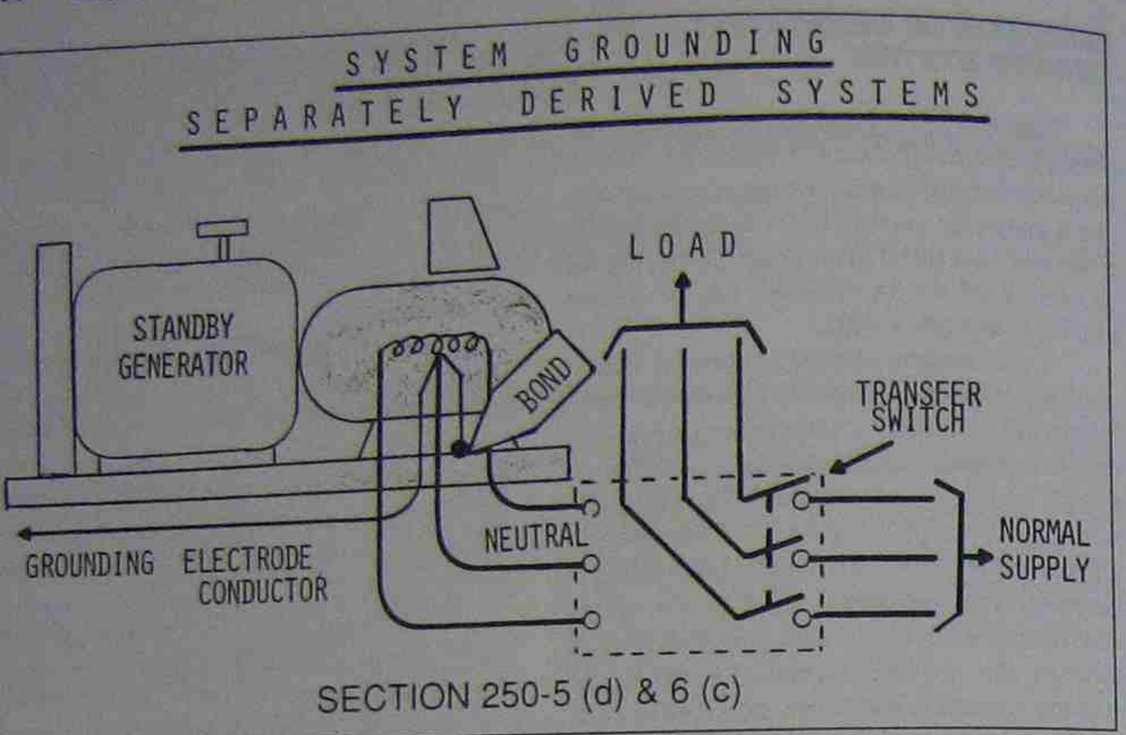
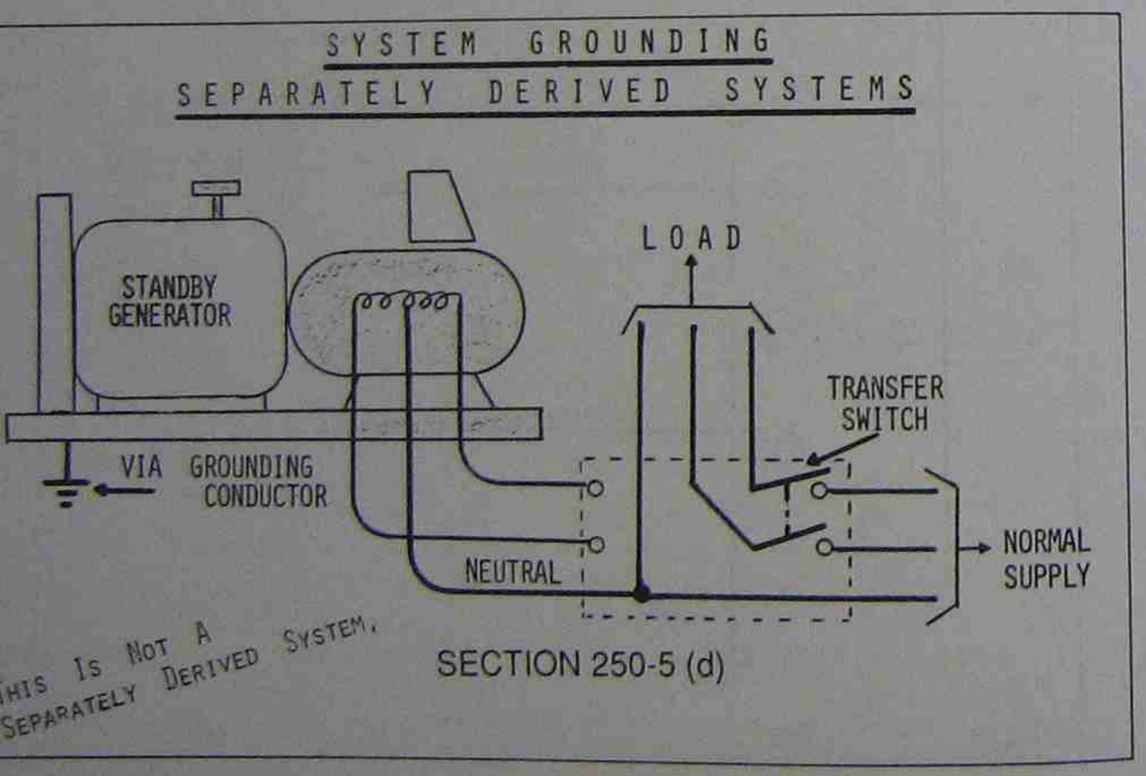


Fig. 16–3 A standby generator with a transfer switch switching the neutral.



. 16–4 A standby generator where the transfer switch does not switch neutral. It is not a separately derived tem.

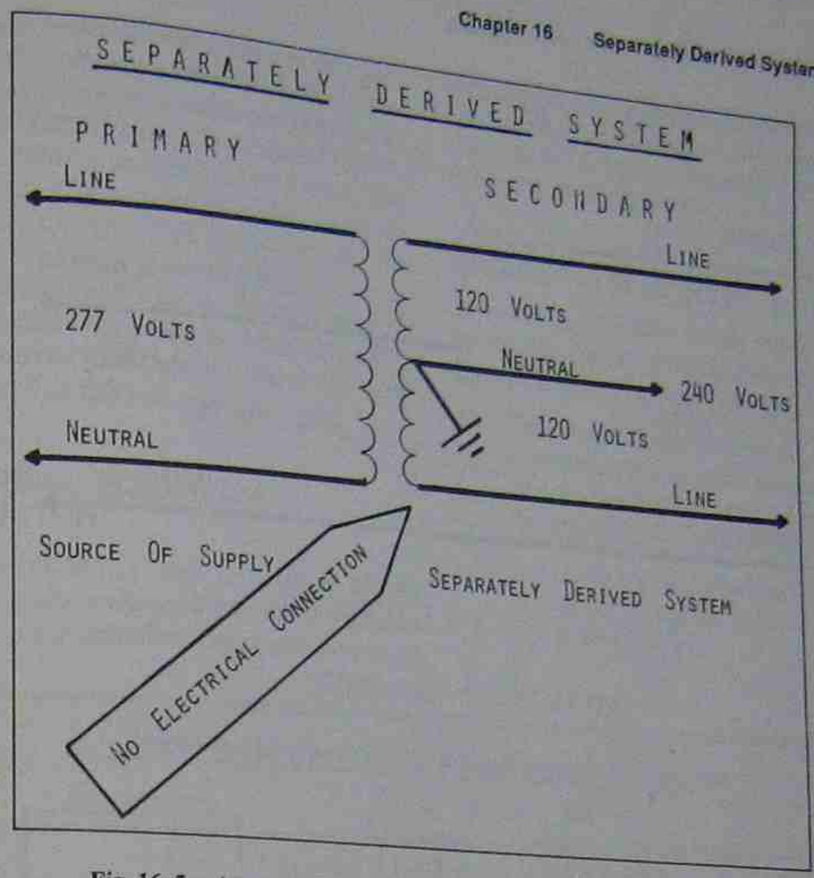


Fig. 16–5 A separately derived system with a single-phase transformer.

the field between the conductors feeding the primary and the distribution conductors of the secondary. The transformer is the most common separately derived system the average electrician will install.

Figure 16–6 illustrates an autotransformer, which has one conductor that is common to both the primary supply and the secondary supply. The 240-volt secondary of the transformer is not a separately derived system because one of the conductors is common to both the supply and the load.

Although a separately derived system is not considered a service and the Code does not describe it as such, it can be considered the same as a service for most practical purposes and, with very few exceptions, it can be treated as one. Compare the following points covered in *Section 250-26* with the requirements for grounding a service.

1. A main bonding jumper is required.
2. A grounding electrode is required.
3. A grounding electrode conductor is required.
4. All grounded conductors present at the source of supply shall be connected together.

MAIN BONDING JUMPER

Figure 16–7 illustrates a separately derived system feeding a panel without any overcurrent protection. The main bonding jumper is installed at the transformer, as permitted by *Section 250-26(a)*. The connection of the main bonding jumper, the grounded conductor (the neutral), the grounding electrode conductor, and the equipment grounding conductor is made at the transformer.

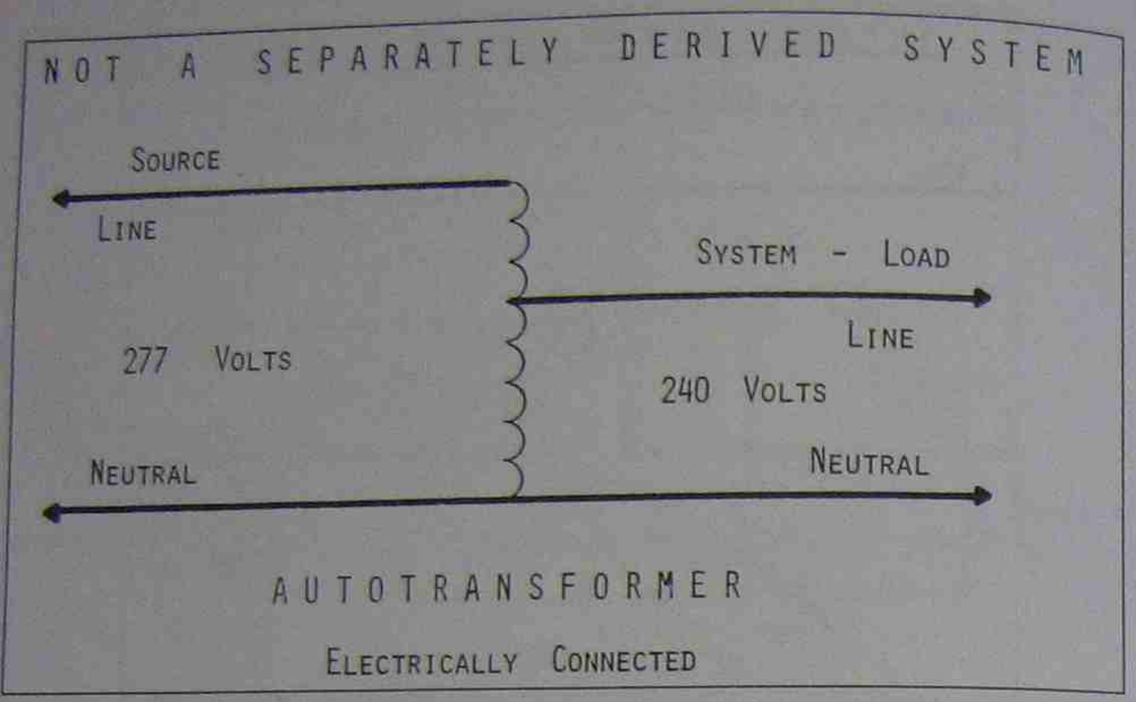
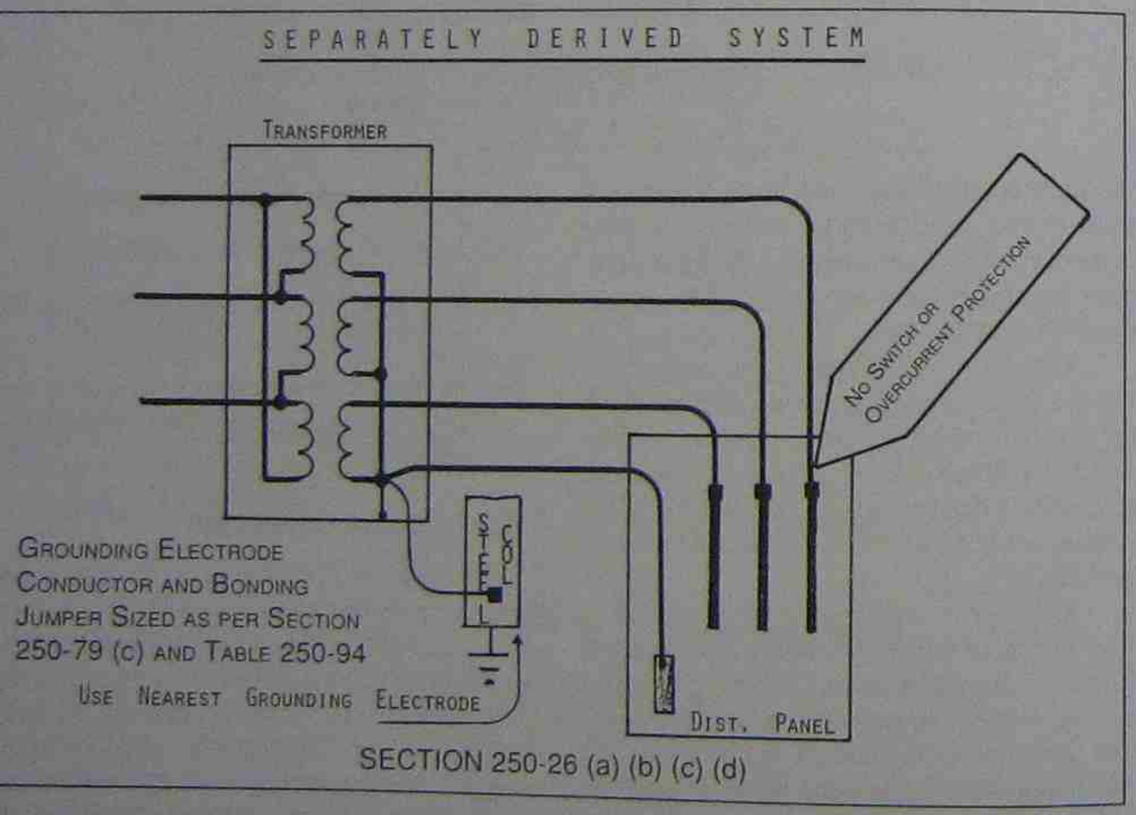


Fig. 16–6 An autotransformer is not a separately derived system.



. 16–7 A separately derived system with the main bonding jumper and grounding electrode conductor nnections made at the transformer.

Figure 16–8 illustrates a separately derived system feeding a panel, with the feeder terminating in an overcurrent protective device. The main bonding jumper is permitted by *Section 250–26(a)* to be installed in the panel. The main bonding jumper, the grounding electrode conductor, the grounded conductor, and the equipment grounding conductor are all connected together at the panel. The main bonding jumper is sized according to *Section 250-79(c)* for the derived phase conductors, as discussed in chapter 9 of this text.

GROUNDING ELECTRODE CONDUCTOR

The materials and installation of the grounding electrode conductor are the same as for a service installation. The conductor is sized according to *Table 250-94* for the derived phase conductors. The connection of the grounding electrode conductor can be made as illustrated in figures 16–7 and 16–8.

GROUNDING ELECTRODE

Section 250-26(c) covers the special requirements for the grounding electrode for a separately derived system. These are:

1. The grounding electrode shall be located as near as practical to the grounding conductor connection (the grounding target of the separately derived system).
2. Preferably it shall be located in the same area as the grounding conductor connection to the system.

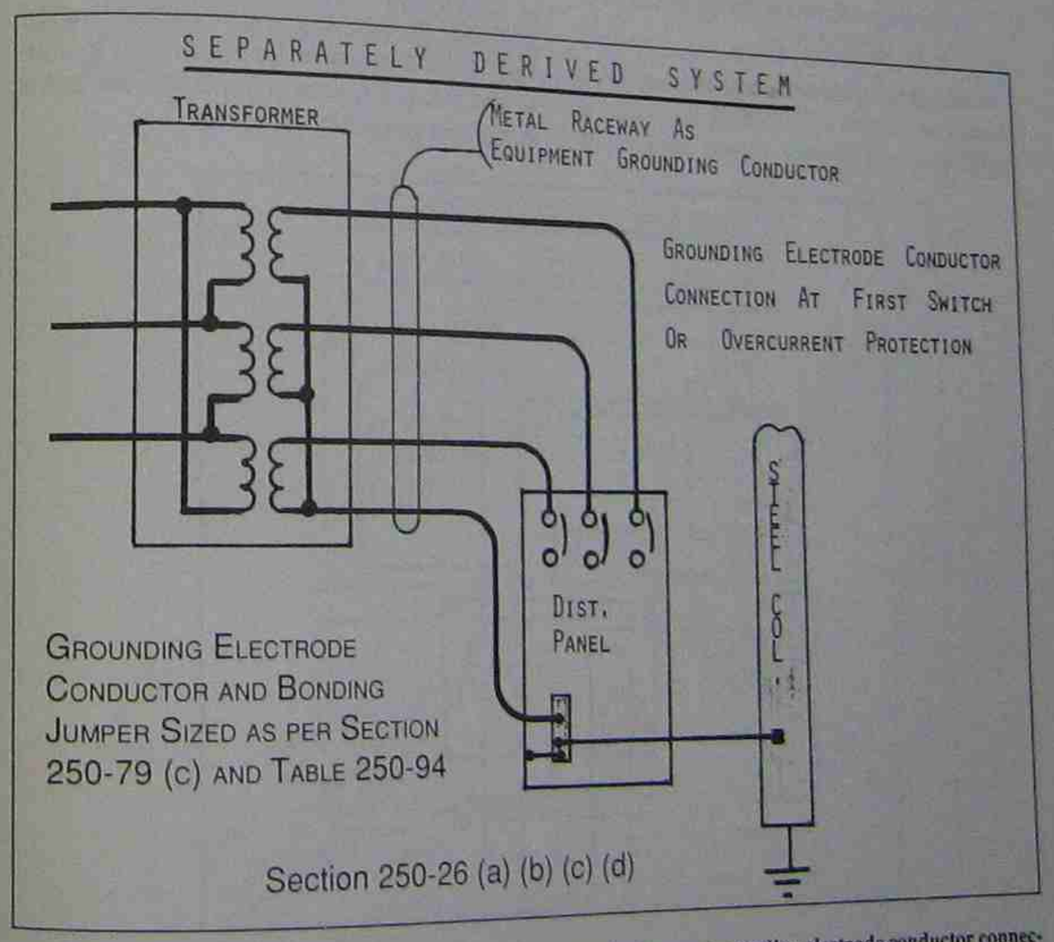


Fig. 16–8 A separately derived system with the main bonding jumper grounding electrode conductor connections made at the first disconnecting means.

3. The grounding electrodes are listed in this section in order of preference. They shall be

   a. nearest the effectively grounded building steel,
   b. nearest the effectively grounded water pipe,
   c. other electrodes as specified in *Sections 250-81* and *250-83*.

There are two things here that are a bit ferent. These are:

. The grounding electrode should be as near as possible to the separately derived system.

. The structural steel and the metal water pipe are preferred over the use of other grounding electrodes listed in *Sections 250–81* and *250–83*.

The grandfather or saving clause is last; it ears in *Section 250-26(d)*. It says that if thing is not covered in this section for grounding separately derived systems, the grounding methods used shall comply with the requirements set down in other parts of the Code.

DEDICATED FIVE-WIRE SYSTEM

The terminology *five-wire system* is being heard more and more. The term indicates a grounded system with an insulated equipment grounding conductor carried throughout the system and the system installed in metal conduit. The metal conduit is not used as the equipment grounding conductor; a separate insulated conductor is installed in the conduit. Figure 16–9 illustrates the use of a separately derived system furnishing a five-wire system. Such a system is used in conjunction with computer and data processing equipment.

CAUTION: The metal conduit system enclosing the five-wire system with the equipment grounding conductor installed in it is installed just as if it were going to be used as the equipment grounding conductor.

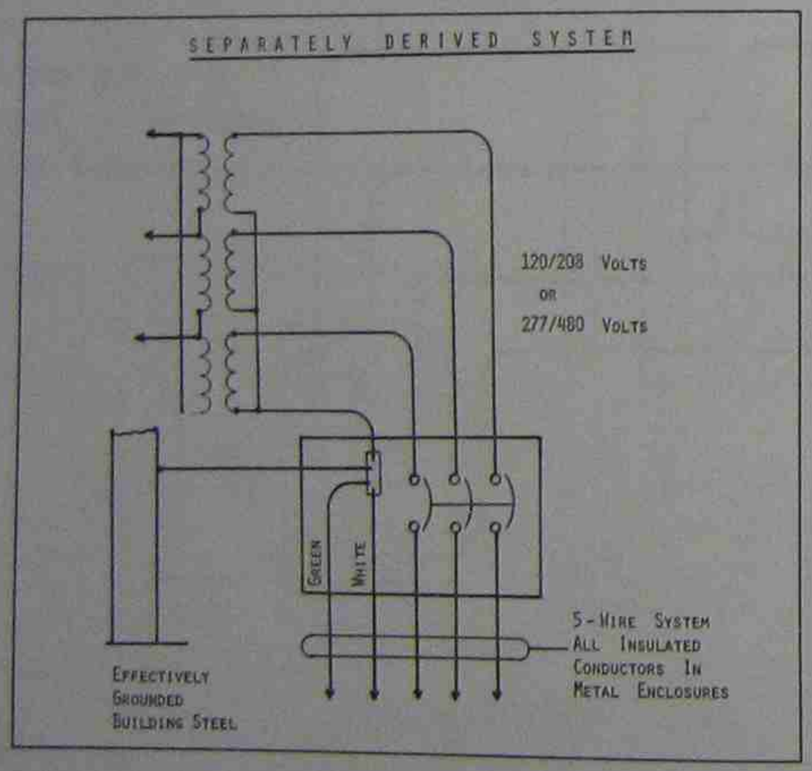


Fig. 16–9 A separately derived system furnishing a five-wire, wye connected system with an insulated equipment grounding conductor.

PORTABLE GENERATORS

Figure 16–10 illustrates a generator for a separately derived system. The generator has a neutral conductor and is required to be bonded to the frame of the generator, according to *Section 250-6(c)*. Such a system could be installed in a remote area where there is no utility company distribution, or it could be used for temporary power.

According to *Section 250-6(a)*, the frame of a portable generator is permitted to be the grounding electrode (figure 16–10) when it is the supply system and provided all the following conditions are met:

1. The generator supplies only equipment mounted on the generator and/or cord- and plug-connected equipment through receptacles mounted on the generator.
2. The noncurrent-carrying metal parts of equipment are bonded to the generator frame.

3. The equipment grounding conductor terminals of the receptacles are bonded to the generator frame.

VEHICLE-MOUNTED GENERATORS

The frame of the vehicle on which a vehicle-mounted generator is mounted is permitted to be the grounding electrode (figure 16–11) when it is the supply system and all the following conditions are met:

1. The frame of the generator is bonded to the vehicle frame.
2. The generator supplies only equipment mounted on the generator.
3. The generator supplies cord- and plug-connected equipment through receptacles mounted on the vehicle or generator.
4. The noncurrent-carrying parts of equipment are bonded to the generator frame.

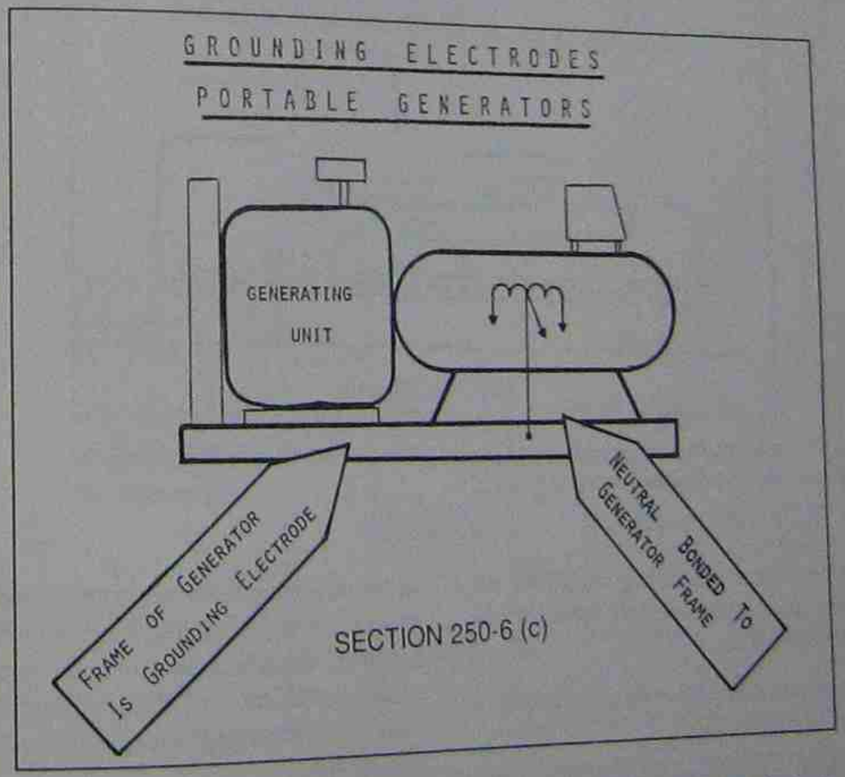


Fig. 16–10 A portable generator frame is permitted to be used as a grounding electrode.

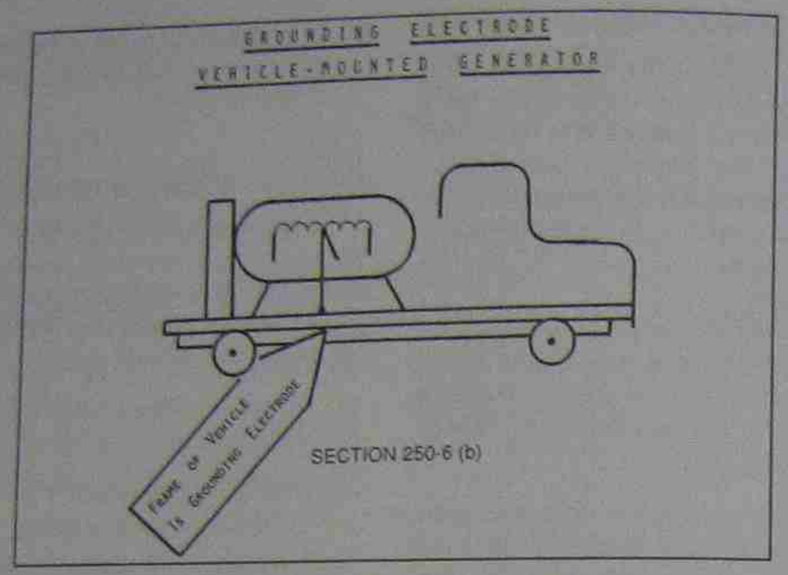


Fig. 16–11 The vehicle frame of a vehicle-mounted generator is permitted to be the grounding electrode.

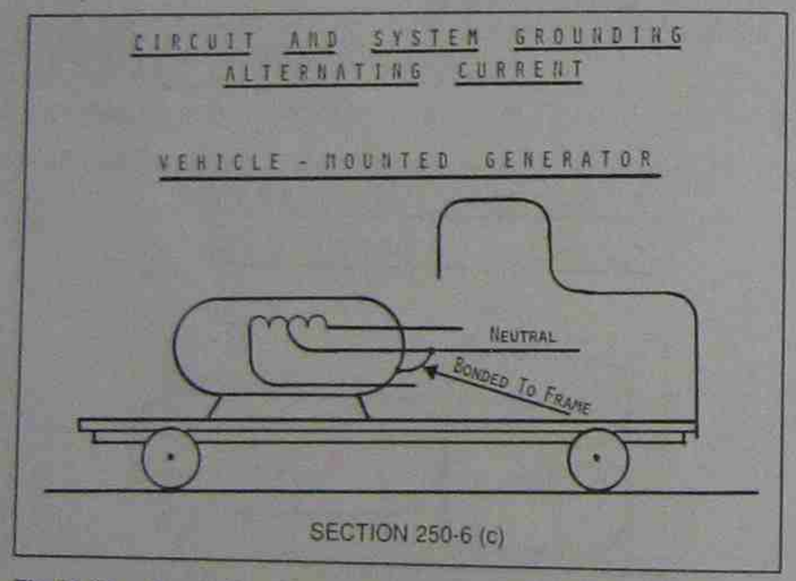


Fig. 16–12 A neutral conductor used with a vehicle–mounted generator. It is bonded to the generator frame.

5. The equipment grounding conductor terminals of the receptacles are bonded to the generator frame.
6. The system complies with all other provisions of *Article 250*.

Permission to use the frames of the portable generator and vehicle-mounted generator as the grounding electrode is an example where ground can be something other than earth. Figure 16–12 illustrates *Section 250–6(b)*, where a neutral conductor is used in conjunction with a vehicle-mounted generator and is bonded to the vehicle frame.

CHAPTER 17

Two or More Buildings Supplied By One Service

This chapter focuses on installing a common electrical service for two or more buildings or structures on the same premises. Although there could be more than two buildings and/or structures, this chapter uses two buildings for illustration purposes. The same regulations that apply to the second building also apply to a third, fourth, or any number of buildings or separate structures installed on the same premises and fed from one common service.

When one service serves two buildings, there are some special Code regulations that apply to the grounded conductor (the neutral) and the equipment grounding conductor.

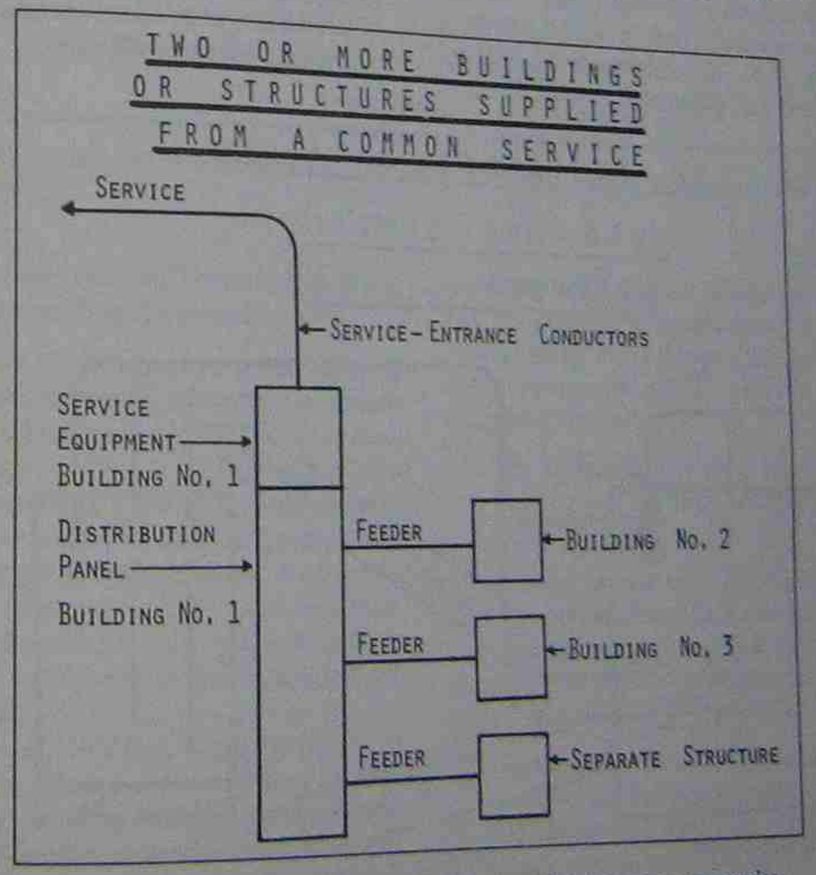


Fig. 17–1 Two or more buildings or structures supplied from a common service.

A helpful hint or a rule of thumb when two or more buildings or structures are supplied by one service is to think of it in the following terms, as illustrated in figure 17–2: Treat the conductors leaving the first building as a feeder and treat the same conductors, when they arrive at the second building as service-entrance conductors, as terminating in service equipment.

The Code does not contain this statement, but in a practical way this is what is taking place. When the feeder arrives at the second building and the system is a grounded system, it can be treated as a new service.

GROUNDED AND UNGROUNDED SYSTEMS

The rules for two buildings supplied from one service are set down for both the grounded system in *Section 250-24(a)* (figure 17–2) and the ungrounded system in *Section 250-24(b)* (figure 17–3). The variation in the rules for grounded and ungrounded systems is small. Anything required for a grounded system is also required for an ungrounded system. Exceptions made for grounded systems are also made for ungrounded systems.

When two or more buildings or structures are supplied from one common service (a grounded system or an ungrounded system), the second building shall have a grounding electrode of its own established. *Section 250-24(a)* requires a grounding electrode to be installed at the second building when more than one building or structure is supplied from one common service. The section states the following:

1. The grounded system in each building or structure shall have a grounding electrode.
2. The electrode shall be installed in accordance with Part H of *Article 250*.
3. The grounding electrode shall be connected to the system grounded circuit conductor and the metal enclosure for the building disconnecting means.

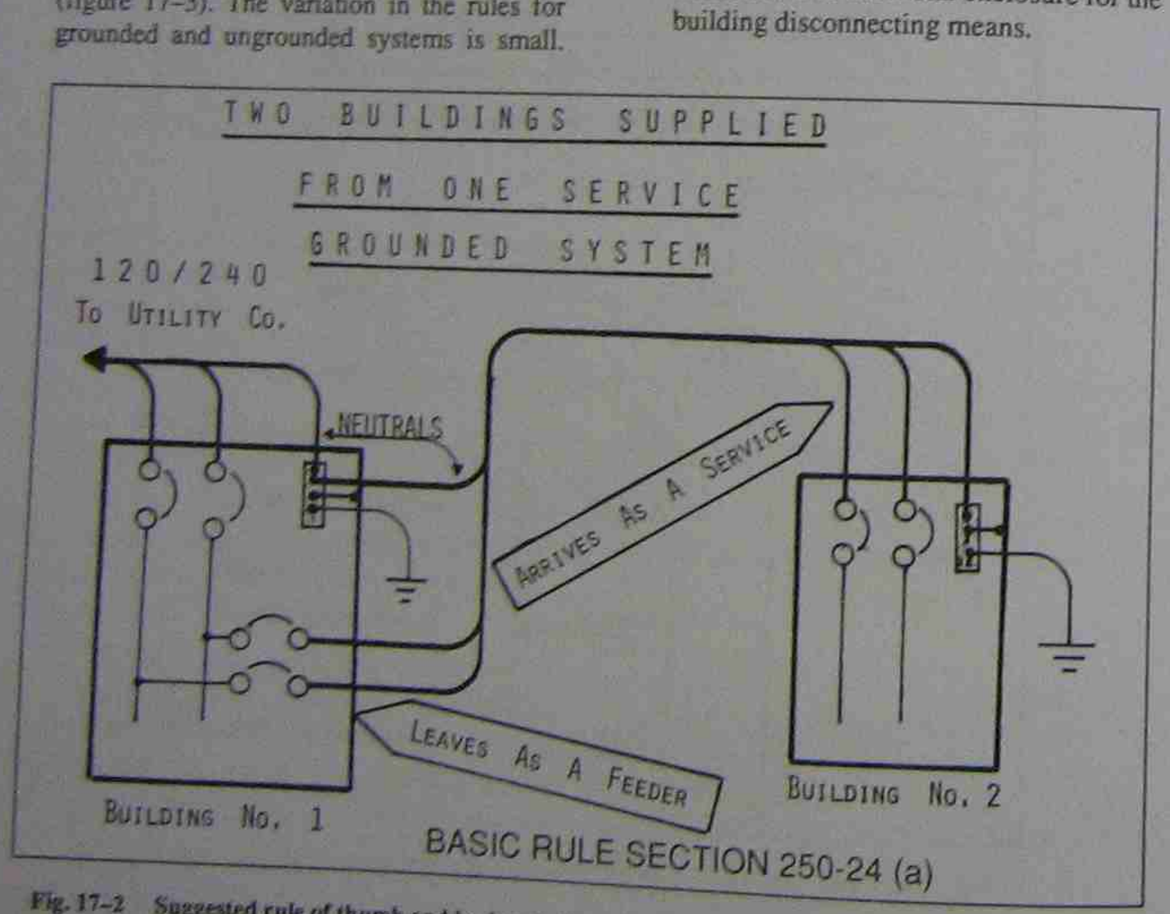


Fig. 17–2 Suggested rule of thumb and basic rule for two buildings supplied from one grounded service.

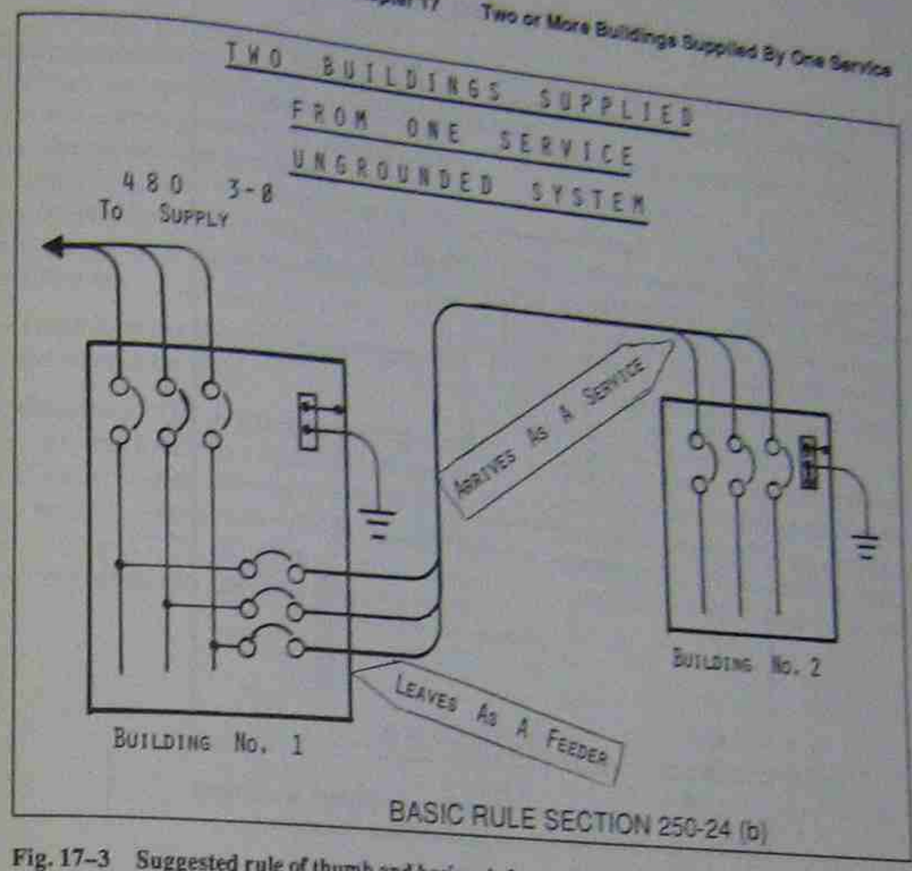


Fig. 17–3 Suggested rule of thumb and basic rule for two buildings supplied from one ungrounded service.

4. The connection shall be on the supply side of the building disconnecting means.

Figure 17–4 illustrates a ground rod being used for the grounding electrode. Any grounding electrode permitted by Part H may be used.

Exception No. 1 of *Section 250-24(a)* permits installing a grounded conductor without the grounded conductor being connected to a grounding electrode conductor at the second building (figure 17–5). This can be accomplished when there is only one branch circuit to be served and there is no equipment required to be grounded.

Section 250-24(a), Exception No. 2 permits the installation of a grounded conductor to a second building without connecting the grounded conductor to a grounding electrode conductor. This installation can be made provided an equipment grounding conductor is also installed from building number one and only one branch circuit is served in building number two. The following paragraphs cover five points required for the use of the exception. Note that all five points must be fulfilled in order for the exception to be used.

1. The equipment grounding conductor is installed with the phase conductors from the first building.

Reason: In case of a ground fault, the impedance of the ground fault path is reduced when the equipment grounding conductor and the circuit conductors are in the same raceway or cable enclosure.

2. The equipment grounding conductor is run to the second building to ground any non-current-carrying equipment, interior metal piping system, and building or structural metal frames.

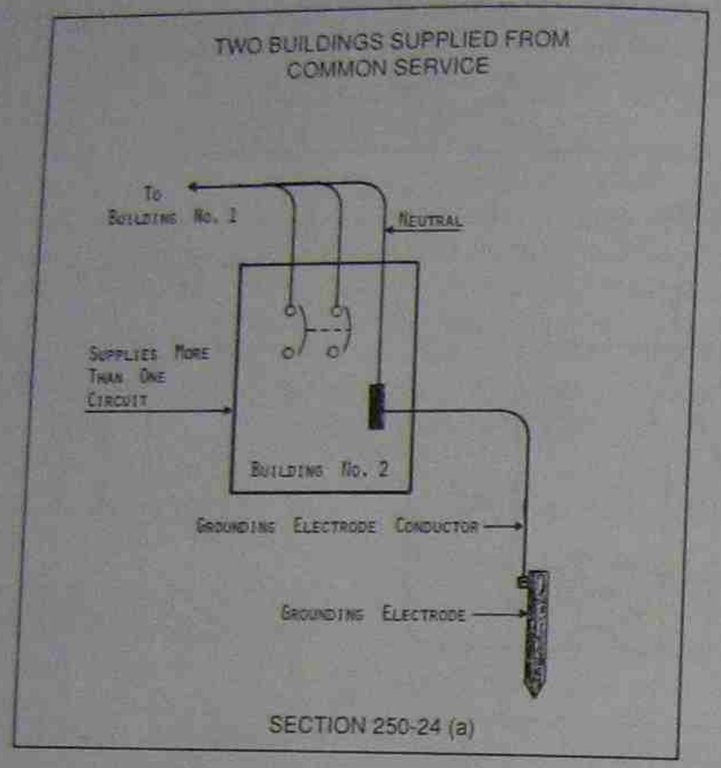


Fig. 17–4 Grounding electrode system established at a second building when two buildings are supplied from one service.

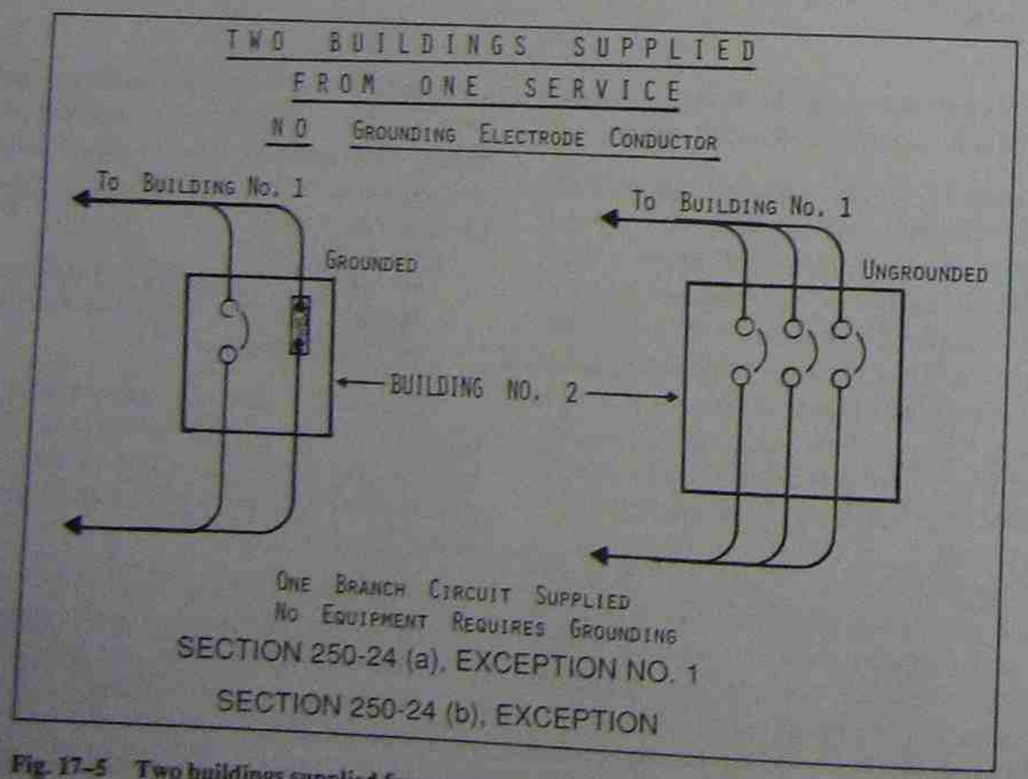


Fig. 17–5 Two buildings supplied from one service when only one branch circuit is supplied.

Comment: This indicates the equipment grounding conductor (figure 17–6) is installed to perform its specific function—grounding noncurrent-carrying metal parts of metal enclosures. The equipment grounding conductor is also used to ground any metal framing that might be present at the second building or in case a steel structure could be used to ground the steel structure.

3. There is no existing grounding electrode in the second building.

Comment: The existing grounding electrodes referred to here are what the Code lists in Part H as grounding electrodes, such as effectively grounded metal water piping or building steel (figure 17–7). If there is an existing grounding electrode, the installation will be in accordance with the applicable sections of *Article 250* for bonding and grounding.

4. There is only one branch circuit in the second building.

Comment: When there is more than one branch circuit in the second building, a grounding electrode system is required. Where there is no effectively grounded metal water piping or building steel, a made electrode shall be installed, such as ground rod or other made electrode.

5. Where livestock is housed in the second building, an equipment grounding conductor run underground to the disconnecting means in the second building shall be an insulated or covered copper conductor.

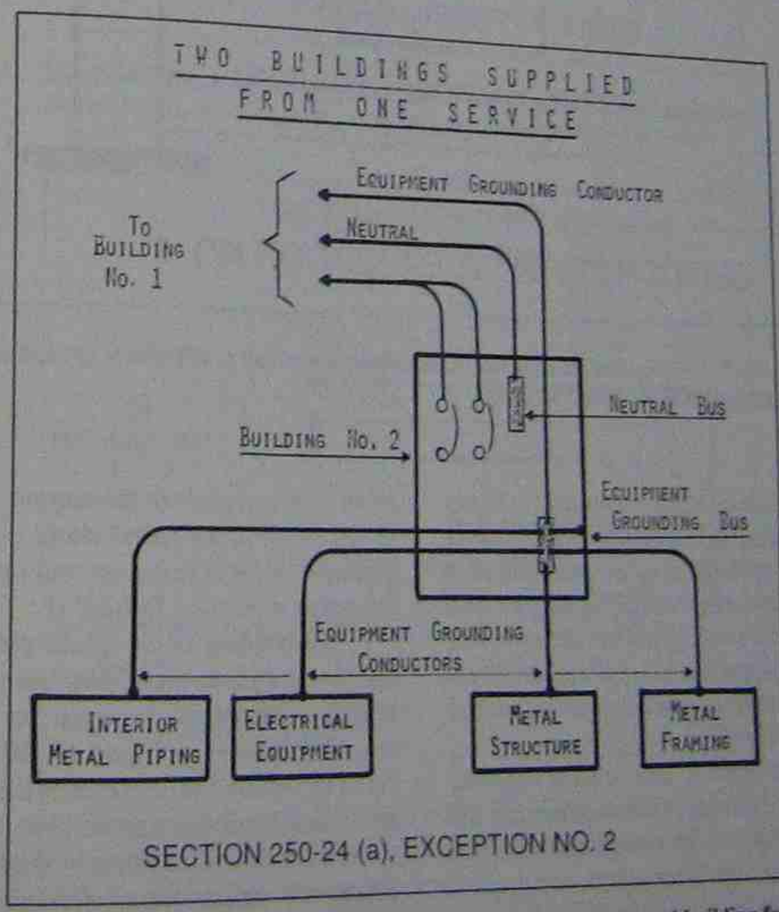


Fig. 17–6 An equipment grounding conductor is run to the second building for equipment grounding.

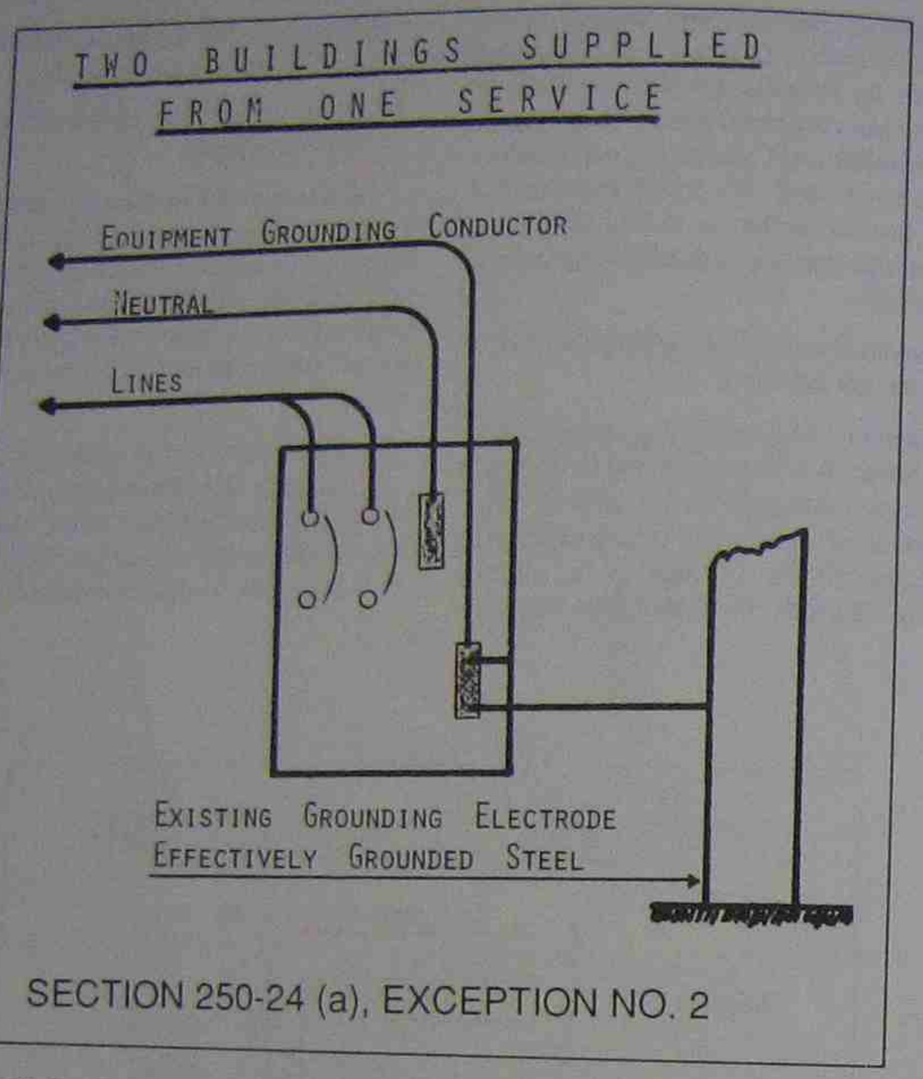


Fig. 17–7 An equipment grounding conductor is connected to effectively grounded building steel in the second building.

Reason: Livestock is very sensitive to any kind of voltage or current caused by leakage or circulating ground currents, and the insulated or covered equipment grounding conductor protects against circulating ground currents. The copper requirement recognizes the durability of copper over aluminum when installed underground (figure 17–8).

The installation of the equipment grounding conductor overhead is not mentioned in this section; therefore, it can be assumed that bare copper or aluminum is permitted.

Should the installation be made using the equipment grounding conductor, and a metal water pipe is present in the second building, as in figure 17–9, the metal water pipe shall be bonded to the equipment grounding conductor, according to *Section 250-80(a)*.

The bonding of the grounded conductor and the equipment grounding conductor at the second building is not required but it is permitted, as illustrated in figure 17–10. Exception No. 2 to *Section 384-27* permits the equipment grounding conductor terminal bar to be bonded to the neutral bar at separate buildings in accordance with the provisions of *Section 250-24*.

CAUTION: This is the only place in the second building where the grounded conductor

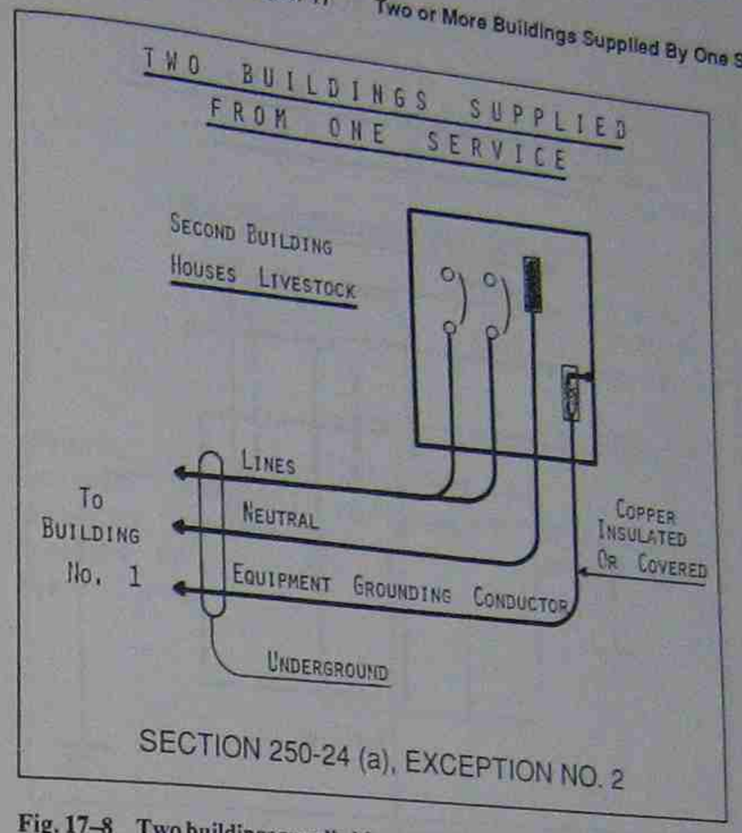


Fig. 17–8 Two buildings supplied from one service when the second building houses livestock.

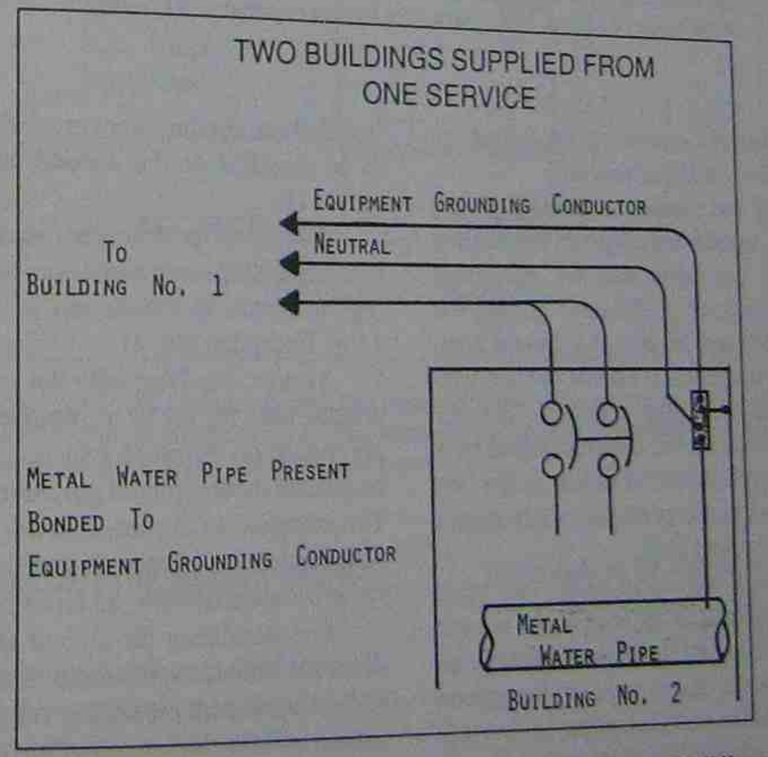


Fig. 17–9 An equipment grounding conductor is run to the second building and bonded to metal water piping.

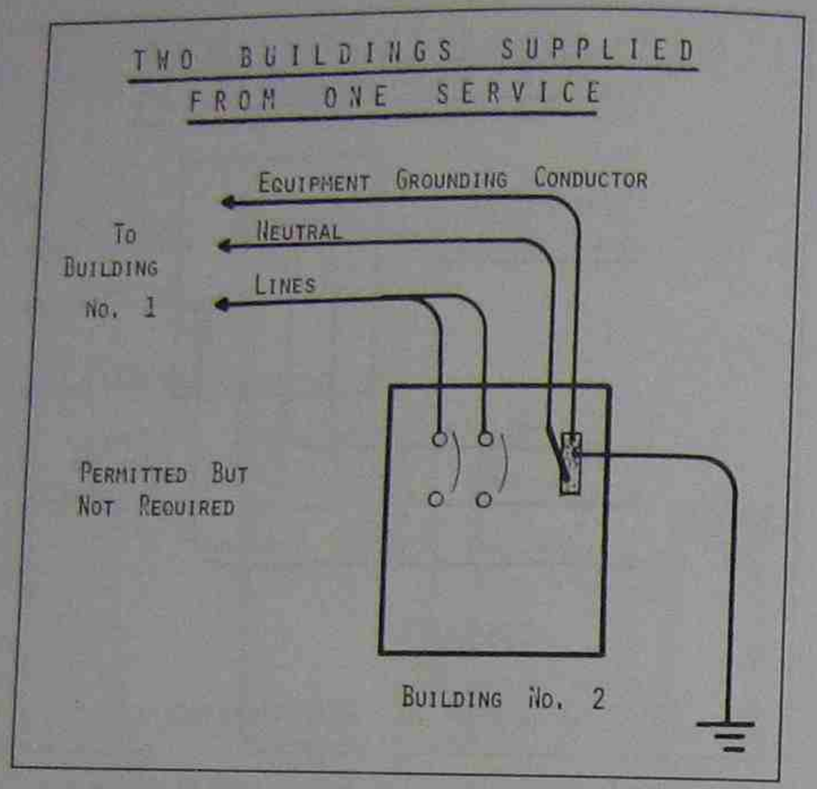


Fig. 17–10 An equipment grounding conductor is run to the second building. The neutral and the equipment grounding conductor are connected together at the second building. This is permitted but not required.

and the equipment grounding conductor are permitted to be connected together.

Installing the equipment grounding conductor to the second building and terminating the grounded conductor and the equipment grounding conductor on the same ground bus offers an advantage. In case of a ground fault, the grounded conductor is now in parallel with the equipment grounding conductor and the parallel path offers a lower impedance path back to the overcurrent protective device in the first building. A lower impedance path offers a quick trip in case of ground fault.

Field installations have found that when ground fault protection of equipment is used with the service in building one and the equipment grounding conductor is run to the second building, the neutral and the equipment grounding conductor need to kept separate to avoid nuisance tripping. A neutral bar needs to be installed and an equipment grounding bar needs to be installed at the second building (figure17–11).

Question: Can the metal raceway run to the second building serve as the equipment grounding conductor, as mentioned in *Section 250-24(a)*, Exception No. 2?

Answer: No. Normally the metal raceway is recognized for use as the equipment grounding conductor, but not in this case. A wire must be used for the equipment grounding conductor. The exception to *Section 250-24(a)* is worded so it requires an equipment grounding conductor to be installed with the circuit conductors.

For calculating the size of the grounding electrode conductor, the main bonding jumper, and the equipment grounding conductor for the second building, the same system of calculation is used that was used for a service or installation in building number one.

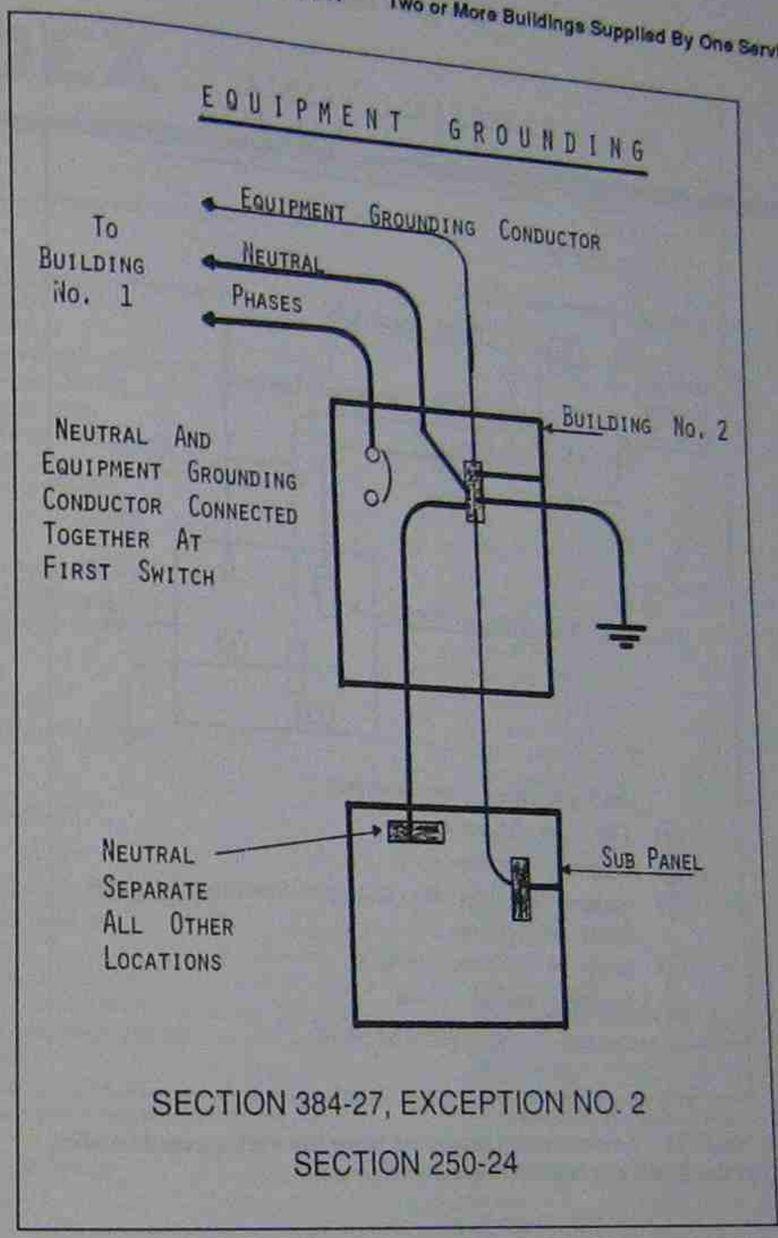


Fig. 17–11 An equipment grounding conductor is run to the second building. The neutral and the equipment grounding conductor are connected together at service of the second building but to no other panels.

AGRICULTURAL BUILDING HOUSING LIVESTOCK

When a second building is used to house livestock and it is supplied by a grounded system, the main bonding jumper at the second building can be omitted, provided that all the following conditions are met (figure 17–12):

1. The supply to the second building arrives at a distribution panelboard.
2. All buildings and premises are under one ownership.
3. The equipment grounding conductor is the same size as the circuit conductors.

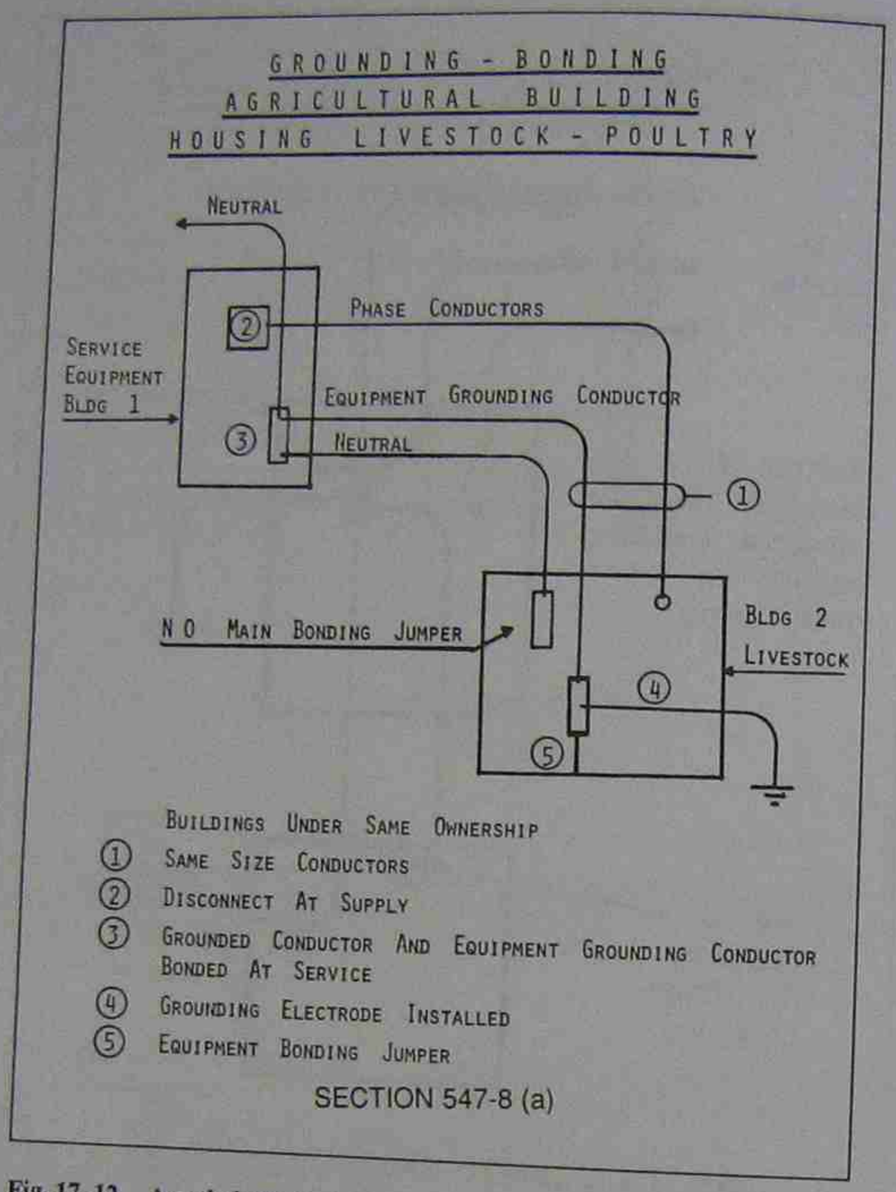


Fig. 17–12 A main bonding jumper can be omitted when a second building houses livestock and special requirements are met.

4. The equipment grounding conductor is run with the circuit conductors.
5. A service disconnect is provided in or near the distribution panel in the second building.
6. The grounded conductor (neutral) and the equipment grounding conductors are bonded at the service equipment at the second building.
7. A grounding electrode is provided and connected to the equipment grounding conductor in the distribution panel at the second building.

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